Université de Toulouse

THÈSE

En vue de l'obtention du

DOCTORAT DE L'UNIVERSITÉ DE TOULOUSE

Délivré par :
l'Université Toulouse III – Paul Sabatier
Discipline ou spécialité :
Génie Electrique

Présentée et soutenue par :
Feng TIAN
Le 06/12/2016

Titre : *Etude et optimisation des systèmes d'éclairage pour la croissance des plantes en milieu contrôlé*

Title : *Study and optimization of lighting systems for plant growth in a controlled environment*

JURY

Pr. Georges ZISSIS	*Directeur de thèse*
Dr. David BUSO	*Codirecteur de thèse*
Pr. Muqing LIU	*Rapporteur*
Pr. Belkacem ZEGHMATI	*Rapporteur*
Pr. Corinne ALONSO	*Examinateur*
Dr. Zéphirin MOULOUNGUI	*Examinateur*
Dr. Christophe MARTINSONS	*Examinateur*
Mr. Thomas PRUDHOMME	*Examinateur*
Dr. Laurent CANALE	*Invité*

Ecole doctorale : *Génie Electrique, Electronique et Télécommunications (GEET)*
Unité de recherche : *LAboratoire PLAsma et Conversion d'Energie (LAPLACE) UMR 5213*
Directeur de Thèse : *Georges ZISSIS et David BUSO*
Rapporteurs : *Muqing LIU et Belkacem ZEGHMATI*

À ma famille

Acknowledgements

As the time flying away, the years shuttling again, three years have passed in a split second, and I will complete my Ph.D. life in lovely Toulouse, France. At the moment, I would like to express my sincere gratitude to Professor Georges ZISSIS, my research supervisor, the director of 'Light and Material' group in Laplace. He has deep insight and understanding on lighting science and technology with focus on the latest light sources, light technology application and light degradation mechanism, and he has done a great work on this domain. Not only the great academic influences, his personality charm: energetic and approachable is being admired greatly. Thank him for his words and demonstrations leading me to the Scientific Palace. I acquired a lot during the three years, which would affect my whole life.

I would like to express my grateful thanks to Dr. Laurent CANALE and Dr. David BUSO. With a cheerful, humorous, hospitable and talkative characters, Laurent give me a colorful time in Toulouse. He is an experienced engineer; not only in my experiments and study, he gave me a favorable guidance, but also helped me much in my daily life. He is my teacher as well as my friend. David works earnestly and responsibly. We did the same project together. He had a keen insight on the research and gave me a lot of helpful suggestions. Without his assistance and guidance, I cannot complete my work very well. I hope the next cooperation with him.

I would like to thank the jury: Pr. Muqing LIU (reviewer), Pr. Belkacem ZEGHMATI (reviewer), Pr. Corinne ALONSO (examiner), Dr. Zéphirin MOULOUNGUI (examiner), Dr. Christophe MARTINSONS (examiner) and Mr. Thomas PRUDHOMME (examiner).

I would like to say thanks to all the teachers and technicians in our group, such as Mr. Pascal DUPUIS, Mr. Manuel LOPES, Mr. Marc TERNISIEN, Mr. Cédric RENAUD, Mr. Jean-Luc, Mr. Gérald LEDRU, etc. It is my great honor to work with them. They are all my role models to learn how to do the scientific research.

I thank my dear colleagues: Angel BARROSO, Benoit BLONDEL, Benjamin RAMOS, Sovannarith LENG, Alaa ALCHADDOUD, Urbain NIANGORAN, Yuan ZHANG, Xiaolin HUANG, Bo QIAO, Lumei WEI, Chenjiang YU, Song XIAO, Dongxi HE, Fang LEI, Linlin ZHONG, Fei WANG, Xi LIN, Li WU, Tianyi LIU, Wencong ZHANG, Jingyi WANG, etc. It is indeed my pleasure to exchange experiences and cooperate with them. Thus, I could improve my work quality and efficiency, and complete my thesis in time.

I appreciate the assistance and advice from the engineers of LAPLACE, such as Jacques SALON, Stéphane MARTIN, Nordine OUAHHABI, Vincent BLEY, Cédric TRUPIN, Céline COMBETTES, etc. Without your kindly help, I cannot complete the experimental design and measurements.

I appreciate Biosentec company for the financial and biotechnical support, so we can complete the biological experiments and project.

I thank the teachers and classmates in INRA for the help of biological science and technology, such as Dr. Hua WANG, Dr. Zhongtao ZENG, Yanwei HAO, Hong YU, Qiang LI, Liyan SU, Binbin ZHOU, Gaofei JIANG, Xiaoyang ZHU, Guojian HU, Baowen HUANG, Tongming WANG, Yi CHEN, etc.

I must thank University Paul Sabatier (UPS) of Toulouse, National Center for Scientific Research (CNRS), Laboratory on Plasma and Conversion of Energy (LAPLACE), Light and Material (LM) group, which provide an excellent and comfortable academic environment and friendly atmosphere.

I thank professor Weibin CHENG, who was my supervisor during my master period. He broadened my horizons and guided me to the bright prospect of my life.

I would like to say thanks to all the members in Laplace and all my dear friends in France and China for their encouragement and support.

Finally, I wish to thank my family for their infinite care and encouragement.

Table of Contents

Abbreviations and Symbols

APC - allophyxoxyanin

ATP - Adenosine Triphosphate

CCFL - Cold Cathode Fluorescent Lamp

CCT - Correlated Color Temperature

CEA - Controlled Environment Agriculture

CFL - Compact Fluorescent Lamp

CFU - Colony Forming Unit

COP21 - 21st Conference of Parties

DFT - Deep Flow Technique

EL - Electroluminescent

EPPF - Equal Photosynthetic Photon Flux

ETMs - Electrical Test Methods

FAO - Food and Agriculture Organization

FWHM - Full Width at Half Maximum

Gtoe - Gigatonne of Oil Equivalent

HID - High Intensity Discharge

HPS - High Pressure Sodium

IOT - Internet of Things

LCD - Liquid Crystal Display

LECS - Light Environment Control Strategy

LED - Lighting Emitting Diode

LR - Lighting Recipe

MDG - Millennium Development Goal

MH - Metal Halide

MIMO - Multiple Input and Multiple Output

MISO - Multiple Input and Single Output

MTTF - Mean Time to Failure

MUC - Microprogrammed Control Unit

NADPH - reduced form of Nicotinamide Adenine Dinucleotide Phosphate

NFT - Nutrient Film Technique

OD - Optical Density

OLED - Organic Light Emitting Diode

OTMs - Optimal Test Methods

PAN - Pesticide Action Network

PAR - Photosynthetically Active Radiation

PARS - Plant Artificial Radiation Sources

PC - Phycocyanin

PE - phycoerythrin

PFAL- Plant Factory with Artificial Lighting

PI - Photosynthesis Irradiance

POR - Power on Reset

PPF - Photosynthetic Photon Flux

PPFD - Photosynthetic Photon Flux Density

PSoC - Programmable System-on-Chip

PWM - Pulsed Width Modulation

RQE - Relative Quantum Efficiency

RTC - Real Time Communication

SPD - Spectral Power Distribution

WFS - World Food Summit

WSM - Wavelength Shift Method

YPF - Yield Photon Flux

D - duty cycle

f - light frequency

T_j - Junction Temperature

I_f - Forward Current

P^B - photosynthesis rate

P_m^B - light-saturated maximum photosynthetic rate

T_c - light/dark cycle

T_d - dark period

T_l - light period

V_f - Forward Voltage

α^B - light-limited initial slope

ε - light fraction

μ - specific growth rate

μ_{max} - maximum specific growth rate

Φ_V - luminous flux

General Introduction

Artificial lighting systems can be used for plant growth in controlled environment agriculture (CEA, also called protected horticulture). Their main function is to improve the quality and quantity of agricultural products. Plant factories and greenhouses with supplemental lighting are the concrete manifestations of CEA. Their development is based on the application of Plant Artificial Radiation Sources (PARS), which means that the sunlight has not been the unique light source for agricultural production but can be replaced by PARS. Especially, Plant Factory with Artificial Lighting (PFAL) is a modern agricultural innovative technology that fundamentally change the concept of farming. How to select the light source and optimize the lighting system for plant growth are of great importance.

However, there are some key issues for this new technique. First, some people do not understand well the characteristics of artificial light sources. Second, photobiology mechanism under different spectra is not clear enough for all the species. Third, agricultural field is a large system of great complexity. As a result, the PARS are improperly selected and usually have low efficiency and high energy consumption, which become the main obstacles for applications.

Lighting emitting diode (LED) is known as the latest light source. Compared with legacy light sources, it has unparalleled advantages such as high efficiency, long lifetime, flexible spectrum, monochromatic light, cool spectrum, small size, robust, etc. Besides, LED lighting systems use DC power supply, which are more reliable and easier to control. Therefore, LED lighting systems become more and more popular to the researchers, design engineers, manufacturers and biologists. Particularly, LED applications for agricultural production also attract broad attention in the world in recent years. LED is an ideal choice to spread in the protected horticulture.

In order to promote agricultural application of LED lighting system, there is urgent demand for understanding LEDs and matched lighting systems. Optimization of LED lighting systems for protected horticulture has great significance for modern agriculture. It is not a lighting system for human eye but a special facility for plant growth. Take the advantage of monochromatic spectrum of LED, and do research on the effect of specific spectrum on plants for the optimal light quality, quantity and photoperiod.

First of all, a lighting system was designed considering generic plants. This part took into account the Relative Quantum Efficiency (RQE) curve, which is actually based on the light response of 22 average photosynthesizing plants. In a second step, we focused on a particular species, *spirulina platensis*, that feature unique characteristics, like fast growing rate and relatively simple metabolism. The second part was supported by the program EPICURE funded by Region Midi-Pyrénées and European FEDER.

The dissertation is divided into the following five parts:

Chapter 1: Introduce the research background and situation of this topic. The key points are focused on the history, characteristics, applications and issues of artificial light sources; it clearly highlights the characteristics and advantages of LED light sources and their applications. The concrete manifestations of controlled environment agriculture, plant factories and greenhouses are introduced; PARS and PFAL are mainly discussed as the core environmental factor for plant growth. Besides, LED based PARS linked to hunger world problems is also introduced, which shows that optimization of LED lighting systems for plant growth has great significance to improve current situation.

Chapter 2: In this chapter, the experimental setup to measure LED characteristics, including electrical, optical, thermal and colorimetric characteristics is presented. The electrical, PAR and spectral models of some LEDs are analyzed. Results obtained was then used as a basis to design the LED lighting system for plant growth.

Chapter 3: According to the characteristics of LEDs, a specific LED lighting system is designed for greenhouse plants. We chose five LED colors: red, amber, green, blue and white within PAR to match the useful spectrum of plant growth. The design principle and process is described in detail. The system chart, schematic diagram and its basic functions are presented. Two operating modes of the system can be available, automatic and manual mode, which can flexibly change the forward current, frequency, duty cycle and period. The system can be programmed based on the characteristic of selective light absorption spectrum for certain plants. Power consumption is also reduced and finally, the system can dynamically adjust the light quality, quantity and photoperiod according the test conditions.

Chapter 4: The spectra of LED is optimized for average plants based on relative quantum efficiency curve. The light efficacy is defined for each channel of the LED lighting system. Different light measurement systems for plants are described including photosynthetic photon flux (PPF), yield photon flux (YPF) and equal photosynthetic photon flux (EPPF). A relatively new concept of light measurement in the field of horticulture is also described by phytometric system. The light efficacy for plant growth is demonstrated by the application of five kinds of light emitting diode within PAR of 400 to 700 nm. In order to theoretically find the best combination of LEDs, the RQE curve was simulated by Gaussian models according on the principle of additive color mixture. Results suggests that twelve different LEDs are required to accurately reproduce RQE in the range of photosynthetically active radiation (PAR).

Chapter 5: The spectra of LED is optimized for *Spirulina platensis* (*S. platensis*). *S. platensis* is selected as the target plant due to a much shorter life cycle as well as the nutritional and medicinal properties. The light requirement for *S. platensis* is analyzed according to the major pigments and PI (photosynthesis irradiance) curve. The absorbance of *S. platensis* is measured by a special design of test container based on Beer's law. In order to get the optimal spectrum for biomass production, we used various kinds of LEDs with different spectra, intensities, powers, light distributions and patterns to cultivate *S. platensis*. In order to know how light spectrum effect on the pigment of phycocyanin (PC) in *S. platensis*, five different ratios of blue and red light are adopted for the experiment. The improved Monod model and PI model were used to properly evaluate the specific growth rate and photosynthesis rate, which was favorable to understand light-limited, light-saturated, photo-inhibited and photo-acclimated regions. Besides, the economic efficiency is also discussed according two criterions: harvest time and concentration of *S. platensis*.

This thesis will end with the general conclusion and perspectives. In this part the interesting conclusions are summarized for each chapter, such as the most efficient light for plant growth and the best harvest time for *S. platensis* in different light conditions. At last, the future works are anticipated in this domain.

This work was developed in "Lumière et Matière" (LM) research group of Laboratoire Plasma et Conversion d'Energie (LAPLACE), University of Toulouse Ⅲ Paul Sabatier, Toulouse, France. The scholarship of Ph.D. for Feng TIAN is supported by China Scholarship Council (CSC).

Chapter 1
State of the Art

Synopsis

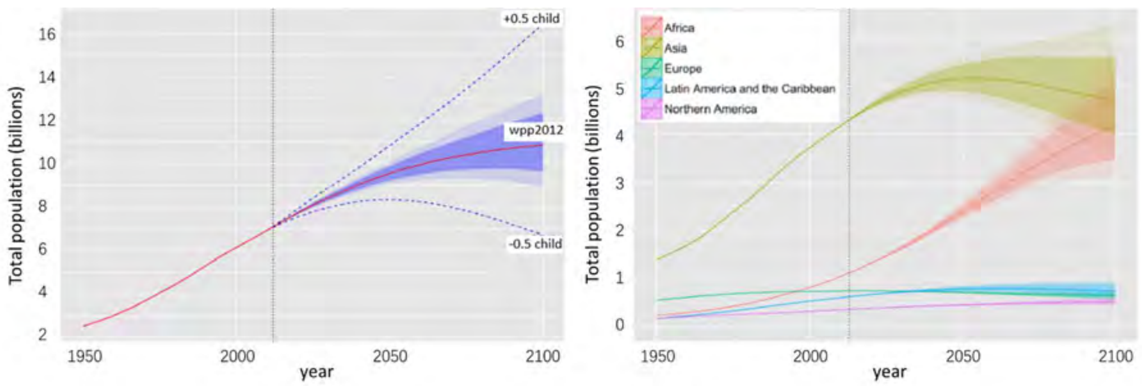
Artificial light sources and lighting systems are the core technology to develop controlled environment agriculture (CEA). In the background of world crises and social issues, CEA can effectively reduce agricultural risk and enhance quality and quantity of production. The key points in this part are focused on the history, characteristics, applications and issues of artificial light sources, clearly highlights the characteristics and advantages of LED light sources and its applications. As the concrete manifestations of protected horticulture, plant factory and greenhouse are introduced. Plant Artificial Radiation Sources (PARS) are mainly discussed as the core environmental factor for plant growth. Optimization of LED lighting systems has great significance to develop protected horticulture, which could be a good production mode to solve the social issues. At last, we chose *Spirulina platensis* as the experimental subject due to a much shorter growth cycle as well as its nutritional and medicinal properties.

1.1 Research background

1.1.1 Population explosion

The United Nations recently released population projections based on data until 2012 and a Bayesian probabilistic methodology. The data reveals that world population will increase from the current 7.2 billion to 9.6 billion in 2050 and 10.9 billion in 2100 (Figure 1-1 (a)). The projections of total population for each continent to the end of the century is shown in Figure 1-1 (b). Asia will probably remain the most populous continent, although its population is likely to peak around the middle of the century and then decline. The projected population of Africa is increasing very fast, which will be up to between 3.1 and 5.7 billion by the end of the century [1].

The larger the population there is, the greater demand for energy and food. The growing needs for daily necessity could not be met by the traditional agriculture technology. If the conventional ideas and production methods are not changed in time, it could lead to serious social problems.



(a) (b)

Figure 1-1 UN 2012 world population projection (solid red line), with 80% prediction interval (dark shaded area), 95% prediction interval (light shaded area), and the traditional UN high and low variants (dashed blue lines) (a) and UN 2012 population projections by continent (b) [1].

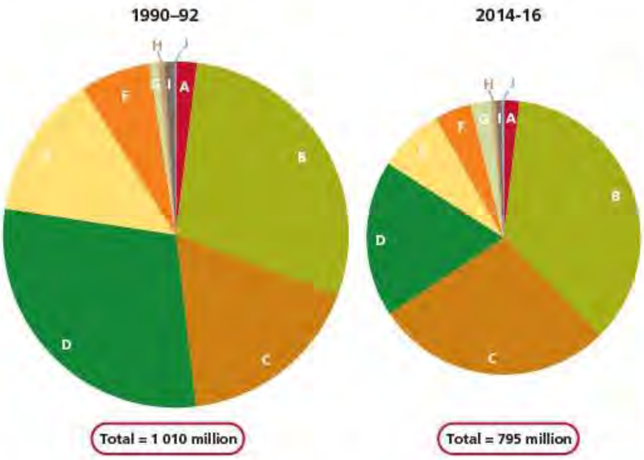
1.1.2 Food supply and security

1.1.2.1 Insufficient food supply

If a person is not able to eat sufficient food to meet the basic nutritional needs, he or she is undernourished. In 2014-2016, the total number of undernourished people in the world is about 795 million (Figure 1-2), which means that over one in every nine people are currently unable to consume enough food to conduct an active and healthy life. The second indicator is the prevalence of underweight children under five years of age. In the developing regions the prevalence of undernourishment and child underweight is about 15% [2].

Paying attention to the insufficient food supply, United Nations members have made two important policies to confront world hunger: The World Food Summit (WFS) in 1996 and the First Millennium Development Goal (MDG) in 2000 with the target to reduce the hanger to half by 2015 [3, 4]. Many countries that have achieved considerable progress, but hunger is still an everyday challenge for 780 million people in the developing countries and 795 million worldwide. In a word, hunger eradication is a daunting task that more efforts should be done to overcome hunger and malnutrition.

The changing distribution of hunger in the world: numbers and shares of undernourished people by region, 1990–92 and 2014–16



	Number (millions) 1990–92	Number (millions) 2014–16	Regional share (%) 1990–92	Regional share (%) 2014–16
A Developed regions	20	15	2.0	1.8
B Southern Asia	291	281	28.8	35.4
C Sub-Saharan Africa	176	220	17.4	27.7
D Eastern Asia	295	145	29.2	18.3
E South-Eastern Asia	138	61	13.6	7.6
F Latin America and the Caribbean	66	34	6.5	4.3
G Western Asia	8	19	0.8	2.4
H Northern Africa	6	4	0.6	0.5
I Caucasus and Central Asia	10	6	0.9	0.7
J Oceania	1	1	0.1	0.2
Total	1 011	795	100	100

Note: The areas of the pie charts are proportional to the total number of undernourished in each period. Data for 2014–16 refer to provisional estimates. All figures are rounded.
Source: FAO.

Figure 1-2 The numbers and shares of hunger and undernourished people in the world [2]

1.1.2.2 Food safety problems

Each year in the United States alone, it is estimated that 76 million Americans suffer from food-borne diseases, more than 33 million people are sent to hospital for food related illnesses, and about 5,000 people die. The cost in lost wages, insurance claims and medical bills amounts to between $7.7 and $23 billion a year [5-7]. Recently, food safety issues have gained national attention. The quality and safety of food for human consumption demand prompt solution.

The food safety problems are mainly as follows:

A. Foodborne Illness–Foodborne illness is still the most prevalent risk with food, largely caused by contaminated food and drinking water wherein diseases bacteria, viruses, prions and parasites. High-density and low-sanitation livestock facilities spread the diseases more rapidly [8].

B. Pesticide Exposure–Pesticides are used in many agricultural operations, but it has the potential to cause adverse human health. Human exposure to pesticides can occur through ingestion of contaminated foods, drinking water, and animal products due to bioaccumulation, inhalation, or skin contact. The Pesticide Action Network UK (PAN UK) (2013) reported that nearly two thirds (63%) of supermarket own-brand loaves and top brand-name loaves analyzed in 2013 contained traces of 1 or more pesticides [9].

C. Food Contaminants–There are many other substances such as heavy metals like lead, mercury, and cadmium are occasionally found in food, which can lead to serious cases of poisoning, as well as related health issues like Minamata disease from mercury and Itai-Itai disease from cadmium [10, 11].

D. Antibiotic Resistance–Emissions of antibiotic residues and resistant bacteria from various human activities, including animal production, fish production, wastewater treatment, and antibiotic manufacturing, will increase the burden of antibiotic resistance in exposed environmental matrices. The abundance and the mobility of antibiotic resistance genes in agricultural soils may be enhanced by various management practices, for example, the application of animal manures, wastewater, or waste treatment residues that contain antibiotic resistance genes on mobile elements and antibiotic residues [12-14].

E. Environmental Effects–Soil, water and air are polluted by irrational exploitation and utilization through agricultural activities. The food quality is also badly influenced. Luckily, with the continuous improvement of awareness, ecological agriculture could be realized by innovative science and technology.

1.1.3 Agricultural economy problems

Currently, agriculture is often subsidized by national government. It seems to be one of the most difficult industries. Farmers often suffer from economic problems, especially in developing countries. However, it still plays an important role for employment and the farmers' main source of income. Farmers focus on maximizing the crop yield by expanding the area of arable and using chemical fertilizers. The phenomenon has led to deforestation and greater environmental cost for little benefit. The quality of crop and soil become worse and worse. This can upset the eco-balance and cause pollution. The destruction of land resources, low productivity and large environmental impact frequently decline agricultural status and income, which lead to market failure.

The poor remain especially vulnerable, as the Food and Agriculture Organization (FAO) has warned repeatedly. The FAO's world food-price index had risen to a record high in early 2011, topping the previous all-time high set in June 2008. As a result, rising food prices have driven an estimated 44 million people into poverty (World Bank, 2011) [15].

Therefore, new agricultural production mode should be adapted to improve the livelihoods and incomes of the poor. It aims to fight hunger and food insecurity, enhancing the productivity of resources, promoting economic integration, and for attaining sustainable progress.

1.1.4 Environmental pollution and climate change

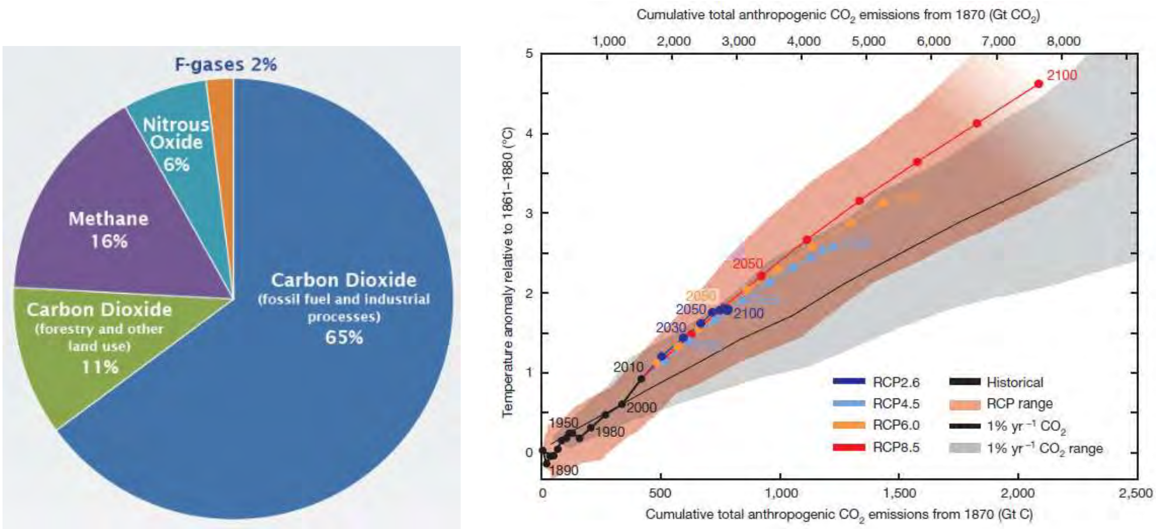
Energy and environment is the foundation of mankind's development. Every citizen has the responsibility and obligation to conserve energy and protect environment.

However, in order to get more natural resources, irrational exploitation and utilization cause serious pollution and destruction of ecological environment, such as the emergence of the greenhouse effect, pollution (air, water and soil), global climate change, species extinction, ozone depletion, desertification, acid rain, deforestation, ocean acidification, transboundary pollution, loss of biodiversity, soil erosion, public health issues, etc. These terrible global environmental issues threaten to the survival and development of mankind.

Carbon dioxide ($\mathrm{CO_2}$) is one of the main greenhouse gases to accelerate global warming. Oil, coal and gas are the principal sources for $\mathrm{CO_2}$ emission (Figure 1-3 (a)). The burning of fossil fuels produces around 21.3 gigatonnes of $\mathrm{CO_2}$ per year, but it is estimated that natural processes can only absorb about half of that amount, so there is a net increase of 10.65 billion tonnes of atmospheric carbon dioxide per year [16, 17]. Measurements of $\mathrm{CO_2}$ from the Mauna Loa observatory show that concentrations have increased from about 313 parts per million (ppm) in 1960 to about 406.81 ppm in 2016 [18]. Besides, the burning of fossil fuels also brought other air pollutants and toxic gases, such as nitrogen oxides, sulfur dioxide, volatile organic compounds and heavy metals, which will destroy the ecological environment [19, 20].

Simulated global mean surface temperature shows the global temperature changes (Figure 1-3 (b)). In the end of 21th century the temperature will increase about 4.5℃ compared with the year 1861-1880. It is a great challenge for the survival of human beings.

So a global movement is under way to reduce CO_2 emission. The pledges and determination demonstrated at the COP21 (21st Conference of Parties) meeting in Paris are likely to lead to further policies aimed at shifting the fuel mix towards cleaner, lower-carbon, fuels, with renewable power, along with natural gas, the main beneficiary [21].



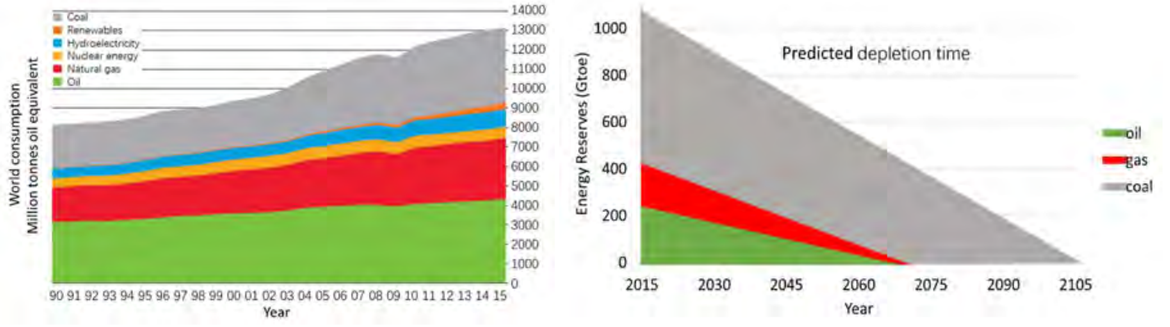
(a) (b)

Figure 1-3 Global Greenhouse Gas Emissions by Gas (a) [22], Simulated global mean surface temperature increases as a function of cumulative total global CO_2 emissions (b) [23]

1.1.5 World energy crisis

Industrial development and population growth have led to a surge in the global demand for energy in the world in recent years. Until now, the world's energy crisis broke out several times from 1970s, which triggered a series of social problems in transportation, finance, business, politics, and even evolved into a war. The price of oil reached the highest of $147.30 per barrel in 2008, and resulted in high inflation with recession [24, 25].

Fossil fuels have been the main energy sources for 200 years, but they are non-renewable and limited resources. Oil, gas and coal remain the world's dominant fuel, about 32.6%, 23.8% and 29.2% respectively in 2015 (Figure 1-4) [26]. Fossil fuel depletion has been identified as a future challenge. According to BP Statistical Review of World Energy June 2016, the total proved reserves of oil gas and coal in the world are 239.4 gigatonne of oil equivalent (Gtoe), 174.1 Gtoe and 624.1 Gtoe in 2015, respectively. At the current consumption rate their deposits will be gone by 2065, 2067 and 2129, respectively. But if we increase production of existing sources (gas or coal) to fill the energy gap left by oil (or gas), the reserves will be finished much faster, taking us to 2102. But the rate at which the world consumes fossil fuels is not standing still, it is increasing as the world's population increases and as living standards rise in parts of the world that until recently had consumed very little energy, so fossil fuels will therefore run out earlier [27, 28].



(a) (b)

Figure 1-4 World energy consumption (a) and predicted depletion time (b) [26]

Oil and coal began to form over 150-300 million years ago, but in the very short period of time (just over 200 years) we've consumed an incredible amount of them, leaving fossil fuels all but gone and the climate seriously impacted [29]. Therefore, new renewable energy sources and technologies need to be developed. If not regulate energy policy and find new production mode, the outbreak of the energy and environment crisis will eventually lead to the destruction of humanity and the Earth.

1.2 Traditional farming vs controlled environment agriculture

Traditional farming was developed in the open field, which was greatly challenged by the world crises and social issues. The quality and quantity of agricultural production are being thrown into doubt. Under this background, controlled environment agriculture (CEA) emerged. Greenhouse and plant factory as two kinds of manifestations are developing very fast. Plant Artificial Radiation Sources (PARS) is a key technique to replace the unique sunlight for plant growth in protected horticulture, which can promote the development of ecological agriculture, and be helpful to solve the relative social issues.

1.2.1 Controlled environment agriculture

1.2.1.1 Definition of controlled environment agriculture

Controlled environment agriculture (CEA), also called protected horticulture, can be defined as an agricultural technique wherein the microclimate surrounding the plants is partially or fully controlled by common or modern facilities during the growing period. The aim of CEA is to provide protection and maintain optimal growing conditions throughout the development of the crop. It not only includes relatively simple greenhouse, but also includes technology-intensive plant factory. Nowadays, CEA is developing very fast in Japan, Netherlands, South Korea, China, United States, Lithuania, Spain, etc. The Netherlands is the country with the most developed technology in the sector. Spain hosts the largest concentration of greenhouses in the Almería region. Japan is one of the most developed countries in terms of greenhouse use [30].

The development of agricultural farming went through 4 stages: traditional uncovered farmland, greenhouse without PARS, greenhouse with PARS and plant factory (Figure 1-5). CEA is the trend to make agriculture from open fields to indoor systems, which will become a competitive and attractive industry.

Figure 1-5 The development of agricultural farming

1.2.1.2 Reasons to develop CEA

The following global crises facing the planet make CEA more and more popular.

A. A growing population in the world
B. Increasing material needs
C. Declining agricultural resources
D. Rapidly growing issues of environmental pollution
E. Climate change and disasters increasing year by year
F. Difficult to guarantee agricultural production systems
G. Prominent food security issues
H. Renewable bioenergy in demand
I. The challenge of urbanization.

1.2.1.3 Characteristics of CEA

Traditional agriculture depends on the natural environment as well as pesticides, chemical fertilizers, antibiotics and other chemicals, but CEA will gradually get rid of these shackles, and ultimately access to high-quality, high-yield, energy efficient and environmental friendly manners [31, 32].

CEA is the combination of physical techniques and agricultural production. The physical factors can regulate growing environment of plants and their growth, such as temperature, humidity, CO_2, light, nutrients, etc. [33, 34]. It is also a high input high output industry and a new production system, which requires equipment, technology and plants be highly correlated. Biological and physical factors are controlled to maximize yield and eliminate the use of toxic and harmful chemicals.

The new technologies are the leader and driving force for development of modern agriculture. These include biotechnology, information technology, water-saving irrigation technology, farming techniques, etc. Modern agriculture makes these technologies become highly intensive industries [35].

The application of agricultural science and technology, firstly, can increase the production units, secondly, can improve the quality of agricultural products, thirdly, can reduce labor intensity, and fourthly can save energy and improve the ecological environment by increased resource utilization and sustainable development capacity. Because the global shortage of resources has become increasingly prominent, agricultural products will become more important, so that the benefits of agriculture may become one of the most promising industries. Modern ecological agriculture has the mission of resource conservation and sustainable development, improving the quality of human life and the living environment.

1.2.2 Commercial greenhouse

The agriculture sector faces the daunting challenge of providing adequate food and other necessities. Unfortunately, there is limited scope for the expansion of cultivated land, and the emerging threat from climate change and other disasters make the task even more challenging [30, 36]. People desire and look for an environmentally friendly and efficient production methods to confront seasonal changes, bad geographical locations, natural disasters, severe weather conditions and so on, so greenhouse has been developed with protection facilities.

Greenhouse is a structure with walls and roof made chiefly of transparent materials, in which plants requiring regulated climatic conditions are grown [37]. There are several kinds of greenhouses such as plastic house, glass house, shade house, lath house, net house and multi-span greenhouse. According to the light conditions, there are greenhouse without PARS and with PARS (Figure 1-6). These structures range in size from small sheds to industrial-sized buildings, and the structures should be sealed heat insulation, but facilitate ventilation and cooling. Before, greenhouse was used in winter to provide a suitable temperature to cultivate plants, and it only used the sunlight as the single energy for photosynthesis. Later artificial light sources have been used as a supplemental light due to insufficient sunlight.

(a) (b)

Figure 1-6 Greenhouse without PARS (a) and greenhouse with PARS (b) (From: http://www.greenhomegnome.com/types-greenhouses-usage/)

Greenhouses are concentrated in two geographic areas: in the Far East (China, Japan and Korea) are grouped 80% of the greenhouses in the world, and in the Mediterranean Basin about 15%. Global area occupied by greenhouses in 1980 was 100,000 hectares, which had increased to 450,000 hectares by 1998; an annual growth close to 20%. Asia accounts for 66% of the area, Europe for 26%, while in America and Africa both account for 4%. By the beginning of the 21st century, the global area of protected crops was around a million hectares; with China accounting for an estimated 700,000 hectares, another 80,000 cultivated in South Korea, Europe and America. Growth is slow in Europe, but in Africa, America and the Middle East, growth ranges from 15 to 20% annually. Notably, China has grown from 4,200 hectares in 1981 to over two million hectares today (30% annually), and has been the country with the largest area of greenhouses. The total areas in major greenhouse production countries are shown in Figure 1-7.

Figure 1-7 Protected crops in the world: over 3 million hectares [30]

Some commercial greenhouses have high-tech production facilities for vegetables or flowers. The greenhouses are filled with equipment including screening installations, heating, cooling, lighting, and may be controlled by a computer to optimize conditions for plant growth [38].

1.2.3 Industrial plant factory

In order to have more living space people construct high-rise buildings, similarly, in order to meet the needs of material life as well as an ecological environment, people can also design plant factories with artificial lighting (Figure 1-8).

Figure 1-8 Plant factory with artificial lighting (From: http://www.odmled.com/news/483.htm)

A plant factory is an indoor vertical farming system for efficient quality food production. It provides information on a field that contribute to offset the threats of unusual weather and shortages of land and natural resources [39]. Plant factory is also a closed plant cultivation facility with physical protection technology, environmental control technology and biological technology as the core technologies, which can control plant diseases and insect pests without using pesticides or other chemicals, and protect the plants from physiological disorders. It mainly includes photosynthetic system, humidity system, temperature system, air circulation system, water and fertilizer system, breeding systems, monitoring and control center, and internet of things (IOT) system (Figure 1-9). The production process is highly intensive. Plant factory has been internationally recognized as an advanced stage of agricultural development; it is an inevitable trend in the development of protected horticulture; it is also one of the most important marks to measure the level of agricultural technology development in the countries [40, 41].

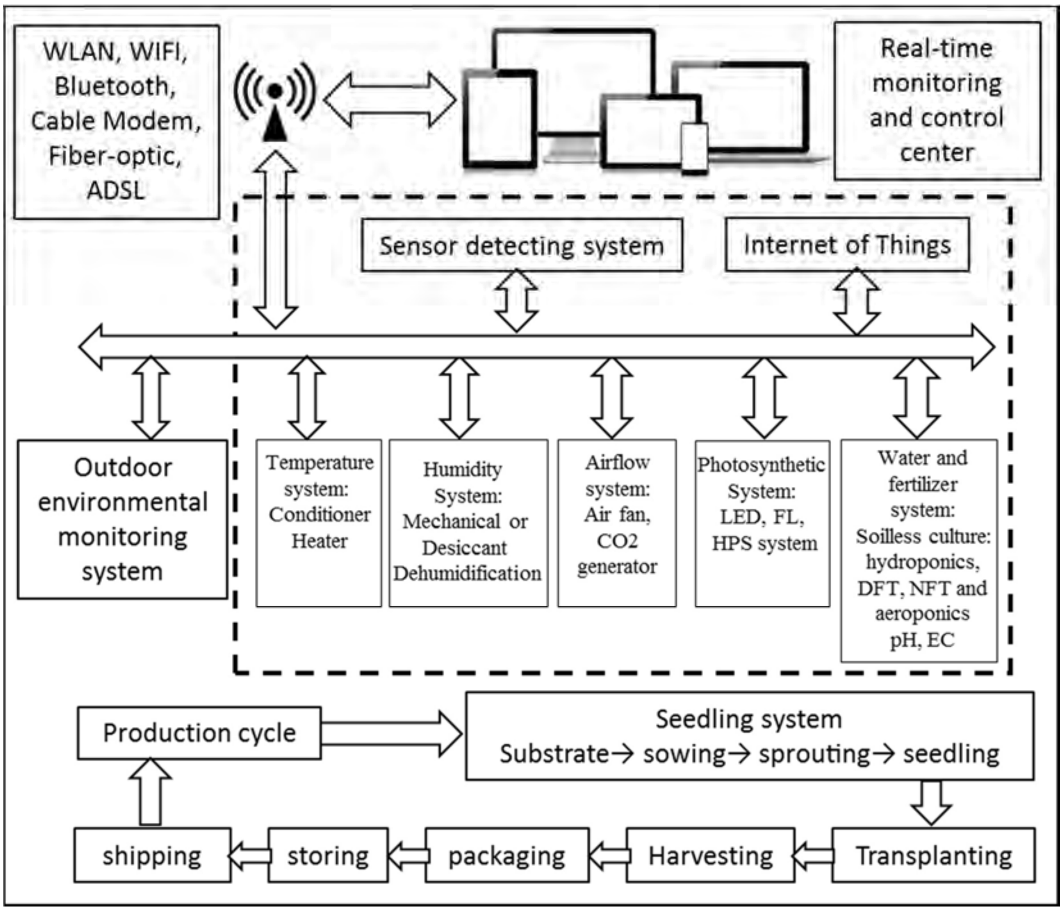


Figure 1-9 The systems of plant factory for production with the core techniques

There are many reasons why plant factory is becoming a new hot spot for investment:

A. Environmental pollutions lead to food safety issues. For example, the abuse of pesticides, insect repellents, fertilizers and hormone; heavy metal and water pollution caused by industry.
B. Traditional agriculture cannot adapt to climate change such as water scarcity and land desertification
C. Urbanization has brought urban population increase, so land resources are dwindling. The demand for agricultural products is on the increase each year.
D. Logistics costs of urban vegetable supply become higher and higher. The prices of agricultural products also rise a lot.
E. The costs of LED application are gradually declining; multi-band LED light is available.

Plant factory production systems have a higher controllability and stability compared with greenhouse. It has a significant value in solving the problems of world resources, environment, food security, climate change and extreme weather disasters. In order to create the best environmental conditions and get more efficient production, some new characteristics of plant factory are presented as follows.

A. Plant factory is a closed plant production system, so the growing environment is not or little affected by the natural climate and soil fertility. Unlike greenhouse, it does not use sunlight and has no transparent material as a cover. In fact, plant factory is a technology-intensive factory for plant growth.

B. Plant factory has the ability to achieve constant production all year around, and the powerful productivity is up to 100 times that of field production [42], especially vertical and multi-layer farming systems with the artificial lights, which can greatly enhance the photosynthetic efficiency and land utilization efficiency.

C. The quality of agricultural products such as concentrations of phytonutrients can be enhanced through manipulation of the growing environment, especially light quality. Moreover, the products are pesticide-free, and the bacterial load is generally less than 300 CFU/g (colony forming unit/gram), which is 1/100 to 1/1000 that of field-grown produce [39], so the products have a longer shelf life and do not need to be washed before eating.

D. Plant factory incorporates high technology and modern science, and can realize precise control of micro-climate by climate controllers and computers. The environmental factors can be manually set and controlled including light, temperature, humidity, wind, pH, carbon dioxide, nutrients and so on. The facilities can be adjusted or programmed according to the climate needs of plants in different growing stages, even realize the automatic control of the environment for specific species. That is to say high resource use efficiency can be achieved with minimum emission and environmental effect.

E. Plant factory can be built anywhere because neither sunlight nor soil is needed, instead of them are artificial light technique and soilless culture (hydroponics, deep flow technique (DFT), nutrient film technique (NFT) and aeroponics culture) [43]. If plant factory is built near urban areas, it is more convenient and reduce transportation costs.

F. In theory any plant can be grown in a protected environment. Plant factory has the advantage in the cultivation of plant breeding and leafy vegetables. However, economic profitability, management and production cycles have determined that high value cash crops and rare medicinal, vegetables, cut flowers and medicinal herbs are grown this way, such as Dendrobium officinale Kimura et Migo [44]. What plant factory should do is to create appropriate growth environment for specific species.

G. Intelligent plant factory can reduce human activities on the production space of interference and pollution. Automatic production includes: controlling environmental factors, fertilizer supply and deployment, seeding, transplanting, harvesting, etc.

Intelligent control of production factors is the most essential features of plant factory. Development of science and technology laid a good foundation. It is important to note the key points such as the proposal of mineral nutrition theory, soilless cultivation techniques, environmental factors and nutrient monitoring based on the development of computer and sensor technology, and the development of semiconductor lighting technology. Currently, almost all environmental factors of plant factory achieve automatic detection, storage, analysis and intelligent control [41].

Plant factory conforms to the essential connotation of modern agriculture, which is equipped with science and technology. Modern organizational management methods are used for agricultural socialization and commercialization. Especially, information network technology is also used to promote the application of modern elements in agricultural production, narrow the distance between production and the market, greatly expand the space for development of agriculture, and enhance comprehensive services in the supply of agricultural materials, technical guidance, financial services, and actively promote the innovation of agricultural and industrial systems. Plant factory has become a strong competitive industry in the national economy.

1.2.4 Significances of CEA

CEA is an innovative production method and have a potential to solve social problems, assure a sustainable agricultural system and eliminate hunger and malnutrition. It is also the most important indicator of ecological agriculture. Agricultural industry itself can become a good cycle of the ecosystem and become sustainable development.

There are many significances to develop CEA [41, 44].

A. Efficient production of renewable bio-energy can supplement fossil fuel depletion.

B. Appropriate scale operation and intensive production can be adopted for efficient using various inputs, including water, electricity, plastic sheeting, fertilizer, seeds, agricultural machinery, etc. So it can reduce the emission of pollutants and improve the ecological environment.

C. Plant growth is less or no influenced by the external environment and climate, so it is able to solve the problem of national food security, improve the quality of agricultural products, human health and nutrition, and less or not use chemical fertilizers, hormones and pesticides.

D. Full-year production can realize a higher overall productivity, including higher land utilization efficiency and labor productivity.

E. Make agriculture a highly commercialized industry with high agricultural commodity rate (>90%), economic efficiency and market competitiveness. Reduce production costs in order to meet the market demand. Reduce rural poverty and contribute directly to higher incomes and the local economy. Gradually lead the people out of poverty and hunger.

F. Meet the new demand for every kinds of food. For example, food in different seasons and high value products can be available.

G. Provide life-support for scientific explorations on extreme environmental conditions, such as oceans, deserts, mountains, Arctic and Antarctic, space station, Moon, Mars, etc.

1.3 Light sources & lighting systems for CEA

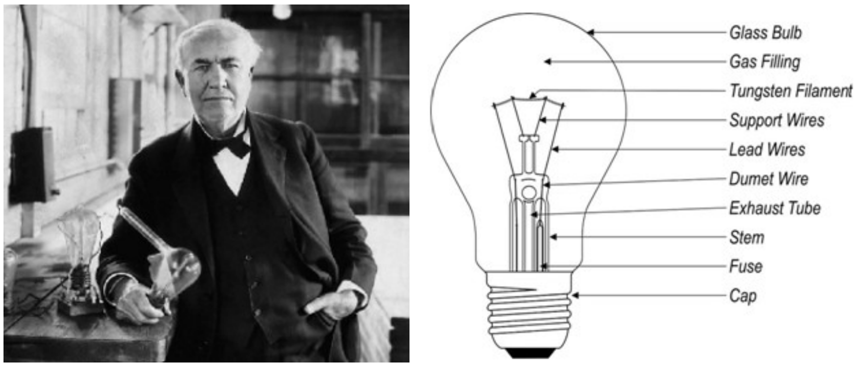
1.3.1 Light sources

There are three major light source technologies: incandescence (incandescent lamp), electrical discharge (fluorescent, HID), and solid state light sources (LED, OLED). The first two are known as “legacy” technologies, and the third is considered as modern technologies. In order to choose the best light source for plant growth, it is necessary to understand the history, characteristics, luminescent mechanism and applicability of typical light sources.

1.3.1.1 Legacy light sources

1.3.1.1.a Incandescent lamp

An incandescent lamp, also called incandescent light bulb or incandescent light globe, is known as the first generation of artificial light source, which was one of the most important inventions since the fires, candles and oil lamps. The first reliable and commercial incandescent lamp was invented by Thomas Edison in 1879 (Figure 1-10), which has already been 137 years of history. It had become a symbol of innovation. It was widely used in domestic and business life before, but now it has been gradually replaced by lamps of higher efficiency.



(a) (b)

Figure 1-10 Thomas Edison with the first incandescent lamp (a) and the typical structure of incandescent lamp (b)

Incandescent lamps include standard incandescent, halogen lamps and reflector lamps. They work by sending electric current through a resistive filament inside a glass or quartz bulb evacuated or filled with inert gas, and heating the filament to a high temperature until it glows with visible light (incandescence). Normally, materials will glow before reaching a melting point. But most materials will melt and cannot make a good filament at a high temperature, so the materials of filament had been the major bottleneck technique [45, 46]. The history of the incandescent lamp was focused on the development of filament types.

From 1802 to 1880s, platinum and iridium filaments were first used for an incandescent lamp. However, blackening on the upward side of the bulb blocked light output. From 1860s to 1883, carbonized threads and paper were developed. Edison doped out a solution to create a pure vacuum with a Sprengel pump by heating up the bulb. He managed to put carbonized threads inside a vacuum and successfully made his first practical light bulb. The breakthrough increased lamp life to 600 hours, so the incandescent lamp was commercially available in 1879. The era of metallic filaments was from 1902 to 1911. Tantalum was the first metal filament and became the king from 1904 to1911. Like tungsten it has a very high melting point, so it can be heated to incandescence with a lower energy and emitted a greater brightness. But after 1909, sintered tungsten lamp became more prevalent. The invention of a ductile tungsten finally terminated the era of tantalum. From 1904 to 1907, there was another filament called GEM Lamp Metallized Filament. A carbon filament was baked at 3000 ℃ to make it like a metal. The efficiency was also improved by 25%. In 1904 sintered tungsten was invented and developed. The lamp efficiency was improved by 100% until 1907.

In 1912 three important improvements were developed to the bulb: an argon and nitrogen-filled bulb, a tight coiled filament, a thin molecular hydrogen coating on the inside of the bulb. In 1921 double coiled filament was developed to further improve luminous efficacy. In 1925 a frosted etched bulb and later in 1947 a silica coating on the inside of the bulb were invented. These advancements helped diffuse the light, reduce glare with only 3-5% loss in light output. All of these dramatically improved the bulb.

In 1955 the first halogen lamp was developed. The halogen lamp has been developed based on incandescent lamp. The striking difference is the filling gas. Halogen lamp contains a halogen gas (bromine or iodine) in the bulb. The tungsten atoms chemically unite with the halogen gas molecules and when the halogen cools, the tungsten is redeposited back on the filament. The process is called the halogen cycle, which has an ability to stop the blackening and slows the thinning of the tungsten filament. This technique lengthens life of the bulb and allows tungsten to safely reach higher temperatures.

From 1908 to the present, tungsten proved to be a superior material for a long lasting light bulb over any other material. Ductile tungsten filament has been the final selection due to its efficiency, durability, bulb life and easily coiled to increase brightness. The invention was also widely used in many other lamps including the fluorescent, halogen, metal halide, mercury vapor, etc. Previous sintered tungsten filaments had been efficient, but brittle and not practical to use.

Although the incandescent lamp has been in the average household for more than 130 years and improved many times, its future is less optimistic. In the last two decades a major initiative to develop more efficient lightbulbs has replaced incandescent lamps in many applications by other types of electric light, such as fluorescent lamps, compact fluorescent lamps (CFL), cold cathode fluorescent lamps (CCFL), high intensity discharge (HID) lamps, and light-emitting diode (LED) lamps. There has been clearly prohibition to use incandescent lamps by many countries according to the rule: phase out of incandescent lamps in 2008 [47].

1.3.1.1.b Fluorescent lamp

Fluorescent lamp is considered as the second generation of artificial light source, which had the greatest development in lighting since the incandescent lamp. There are three main types of fluorescent lamps: cold cathode, hot cathode and electroluminescent lamps [46]. They all use phosphors excited by electrons to create light. The difference is that electroluminescent lamps use fluorescence. It has been widely used in hotels, offices, shops, hospitals, libraries, advertising, family and plant cultivation for 78 years of history since commercial use. Besides, it is also a backlight for LCD displays.

The cold and hot cathode lamps consist of a glass discharge tube filled with an inert gas (usually argon) at low pressure, fluorescent coating on the inside, a tungsten electrode in each side, a ballast only or ballast with starting switch (Figure 1-11). Fluorescent lamps work by ionizing mercury vapor in the glass tube. This causes electrons in the gas to emit photons at UV frequencies. The UV light is converted into standard visible light using a phosphor coating on the inside of the tube. At the beginning, it was a great challenge to start the arc in the discharge tube [48].

The ballast was used to regulate AC current without destroy the lamp. In order to get the lamp started, there must be a spike of high voltage to start the arc, because argon gas itself is a resistance, the colder the gas, the higher the resistance. To reduce the danger and difficulty for a high voltage, preheat the lamp is figured out by using a starting switch. Now there are several ways to start the lamp such as preheat, instant start, rapid start, semi-resonant start and programmed start.

Take the most common preheat way as an example. First, Figure 1-11 shows the AC current (I_{prehe}) passes through the ballast, one tungsten electrode, starting switch and the other electrode in order. At the same time the current warms a bimetallic strip of a small neon or argon lamp inside the starter, and preheats and ionizes some of the gas in the discharge tube. Second, the preheat leads to thermionic emission, and the free electrons ionize the argon gas in the tube. Third, when the starter switch gets warm enough, the bimetallic strip flips the other way and bypasses the small lamp inside the starter. As a result, the open circuit can lead to magnetic field collapse of transformer in the ballast, and produce a high voltage to start the arc (I_{lamp}). After that, the mercury will be vaporized and ionized in the arc tube and create UV light. The phosphors coating inside the glass tube will convert the light into useful visible light.

Compared with DC current, AC current is good for fluorescent lamp to protect tungsten electrodes and emit a nice uniform brightness on both sides. So it can last a long time with AC current.

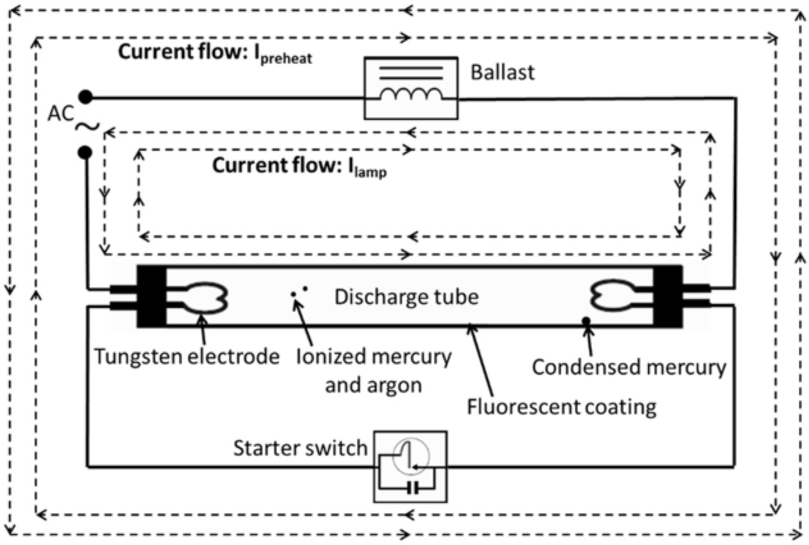


Figure 1-11 The basic structure and work principle of preheat fluorescent lamp

1.3.1.1.c High intensity discharge lamp

High intensity discharge (HID) lamps are known as the third generation of artificial light source. They are also a type of electrical gas-discharge lamp mainly including metal halide, high-pressure sodium, low-pressure sodium and mercury-vapor lamps. HID lamps are applicable for large square.

HID lamps produce light by striking an electrical arc across tungsten electrodes housed inside a transparent and specially designed fused quartz or fused alumina arc tube. This tube is filled with both gas and metal salts. The gas aids in the arc's initial strike. Once the arc is started, the metal salts are heated and evaporated to produce the light, forming a plasma. Like fluorescent lamps, a ballast is necessary for HID lamps to start and maintain the discharge arc [49, 50].

Metal halide (MH) lamp and high pressure sodium (HPS) lamp are the typical HID lamps. They will be mainly introduced in this part.

A. Metal Halide Lamp

Metal halide (MH) lamp is a kind of HID light source. It is popular due to its great color rendering index and high efficiency. The most prominent applications are streets and squares, stadiums, industrial buildings, exhibition centers, shopping malls, docks and railway stations.

Stabilizing the MH lamp arc and color was the main problem in the history. The lamp uses mercury vapor to create the powerful light but includes other halide salts (fluorine(F), chlorine (Cl), bromine(Br), iodine(I) and astatine (At)) to improve the color. A halogen is a monovalent element which readily forms negative ions. A halide is a chemical compound of a halogen combined with an electropositive element.

The argon gas strikes an arc at a low temperature, so the current can pass through the starting electrode to the main electrode (Figure 1-12). The initial arc is weak, and it can heat up the mercury into a vapor. So the more molecules of the gas ionize, the more current passes through the arc. When the arc reaches the other main electrode, the current will stop flowing through the starting electrode. Meanwhile, the halides vaporize and dissociate. The metal atoms diffuse away from the arc and recombine with the halogen before they damage the silica or electrodes. Finally, the lamp is fully warmed up and produces its white light [51-53].

Some critical materials are used for MH lamps. Under a high temperature and pressure, fused quartz is adapted due to a high melting temperature instead of the silica in normal glass. To increase the lifetime, tungsten made electrode is also treated with radioactive thorium. Borosilicate glass is used in the outer envelope to insulate as well as filter out UV-B radiation. Molybdenum is used in the seal of the discharge tube to avoid corrosion and high temperature.

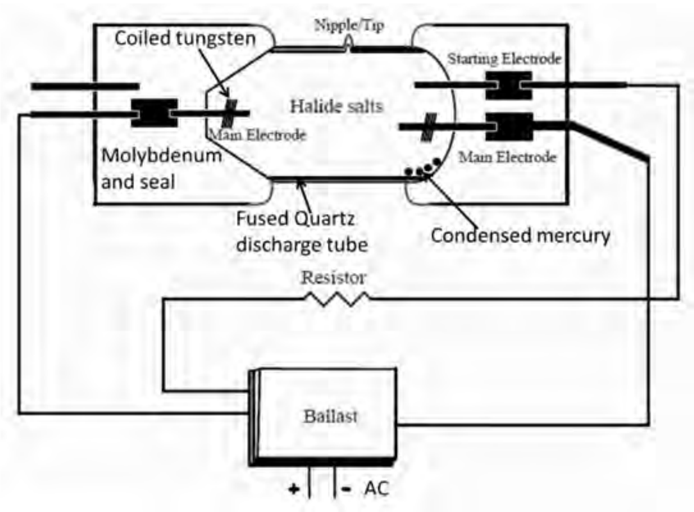


Figure 1-12 The structure of metal halide lamp

B. High pressure sodium lamp

High pressure sodium (HPS) lamp is a kind of HID lamp with high lumen output and high efficiency. It has been widely used in airports, industrial and mining enterprises, parks, highways, squares, streets interchange and plant grow. The basic structure of HPS lamps is shown in Figure 1-13.

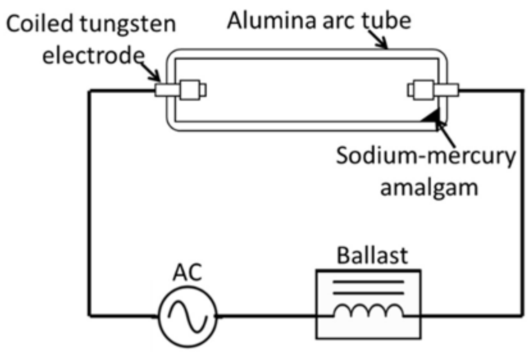


Figure 1-13 The structure of high pressure sodium lamp

The sodium lamp with a higher pressure in the arc tube could achieve a higher efficiency. Which kind of material could stand the corrosive effects of sodium under the high pressure and temperature is the main problem. Later, aluminum oxide ceramic was adopted. HPS lamps consist of a narrow arc tube supported by a frame. Sodium, xenon and mercury are used inside the arc tube. The lamp starts an arc through xenon gas by a pulse of high voltage via a ballast. Then the arc heats up the mercury like MH lamps. The sodium is the last material to vaporize (over 240℃). The mercury helps add a blue light to the pure yellow of the sodium. The sodium is mixed with other impurities to create a nice white light [54, 55].

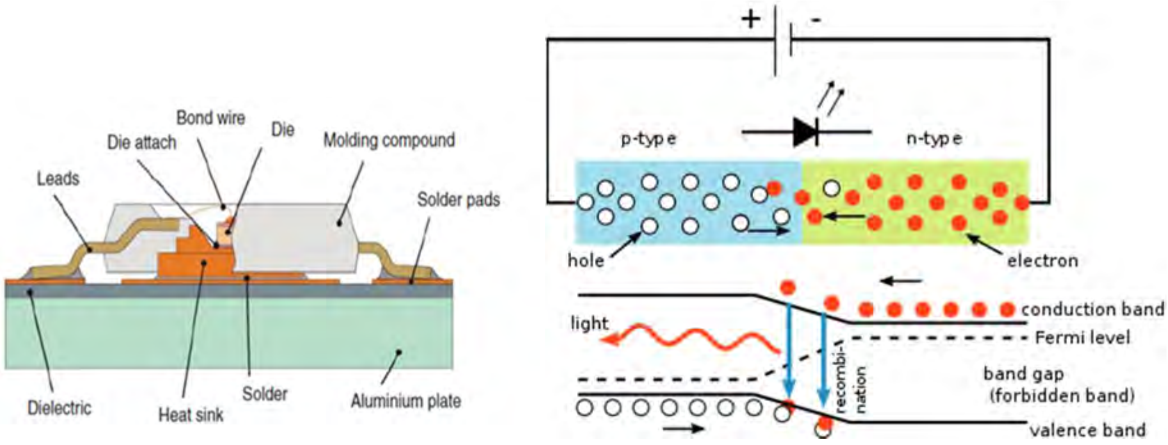
1.3.1.2 Solid state light sources

1.3.1.2.a Light Emitting Diode

Solid state light sources are a kind of Modern light sources, including Light Emitting Diode (LED) and Organic Light Emitting Diode (OLED). LED is known as the fourth generation of artificial lighting source, which has about 60 years of history from the first infrared LED patented in 1961 [56]. In 1962, the first practical visible spectrum LED was developed. The first high-power (1W) LEDs were developed in the late 1990s. It is a new technology and has been developed rapidly in the last decade. Early LEDs emitted low-intensity infrared or red light and often used as indicator lamps instead of small incandescent bulbs. Modern LEDs are available in a broadband wavelength across the ultraviolet (250-380 nm), visible (380-760 nm) and infrared (760-1000 nm), which have been becoming popular due to their high efficiency and brightness. Nowadays, LEDs are used in anywhere, such as indicators and signs, LCD backlight, displays, indoor and outdoor lighting, traffic lights, greenhouse lighting, etc.

LED is a small semiconductor light source (less than 1 mm^2), including a two-lead p–n junction, reflectors, phosphors or integrated optical components to create light and shape its radiation pattern. Figure 1-14 (a) shows one structure of high power LED [57]. The p–n junction is a boundary between two types of semiconductor material inside the same crystal. Like the common diode the p-n junction only allows electrical current to pass through in one direction (from positive to negative), which is called forward-biased. The color of the light emitted is determined by the semiconductor materials and the impurities of the junction [58].

An electron hole exists where an atom lacks electrons (negatively charged) and therefore has a positive charge. With a suitable voltage or current, electrons are able to recombine with electron holes within the semiconductor, releasing energy in the form of photons. This effect is called electroluminescence. The color of the light corresponds to the energy of the photon, which is determined by the energy band gap of the semiconductor (Figure 1-14 (b)) [49, 58-60].



(a) (b)

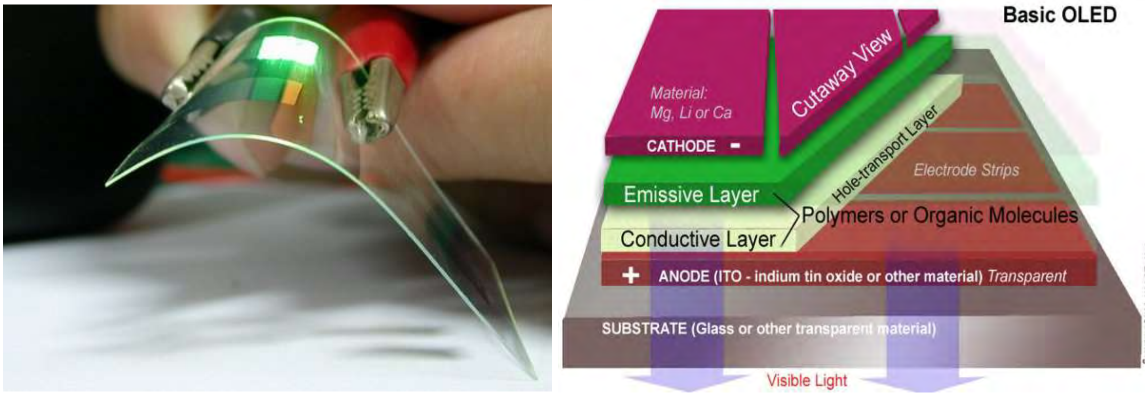
Figure 1-14 Structure of high power LED (a) and light principle of P-N junction (b)

The total cost of a lighting system includes the initial purchase price, the cost of electricity and cost of replacement. In the past, LEDs were often too expensive for most lighting applications. Even though the price of LEDs has significantly decreased over the last few years, it is still much higher than the price of legacy lighting sources. However, this higher initial cost can be offset by the longer lifetimes and better energy efficiency [61]. Yet since the life cycle savings are not guaranteed at the time of lighting system selection, higher initial costs are still an obstacle to the acceptance of LED lighting. According to a study by Samsung, the selling price of a white LED lighting system needs to decrease by 50% in order to make LEDs more competitive with fluorescent lamp systems over the next 4–5 years [62, 63].

1.3.1.2.b Organic Light Emitting Diode

Organic light emitting diode (OLED) is designed by a layer of organic electroluminescent material with p-n junction sandwiched between two electrodes. One of the electrodes is transparent so the photons can escape. The shape of OLED is very similar with electroluminescent (EL) lamps, but they are different. OLED uses organic (carbon) molecules in the layer to emit light, but EL lamps are only excited by phosphor materials to make light. Although the OLED is not as bright as EL display or liquid crystal display (LCD) currently, OLED has been considered as one of the most promising technologies for future displays. OLED has an advantage to better display blacks without a cold cathode fluorescent backlight used for LCD. The OLED display can also provide better contrast ratios than LCD. OLED may also be made into a thin flexible material which could roll up like a newspaper (Figure 1-15 (a)) [60, 64].

Early OLEDs had one layer of organic material between two electrodes. Modern OLEDs are bi-layer, they have an emissive layer and conductive layer sandwiched between two electrodes (Figure 1-15 (b)). When an electric current passes from the cathode to the anode, charges are injected in the organic material, holes from the anode and electrons from the cathode. The holes jump to the emissive layer along the border of the two layers where they recombine with electrons (this place is the p-n junction). After diffusion, the exciton recombines. Light is emitted when the electrons join the holes and a photon is emitted. Polymer LEDs and carbon nanotube technology can expect a lower cost due to the material and less part assembly. However, further study should be done to reach full potential of OLED [60, 64-66].



(a) (b)

Figure 1-15 OLED display (a) and the basic structure of OLED (b) [60]

1.3.1.3 Comparison of different light sources

There are four generations of different artificial light sources (Figure 1-16), and each evolution has made great progress. Compared with fluorescent and incandescent lamps, HID lamps have a higher visible light in contrast to infrared per unit area of envelope. Miraculously, LED has more obvious advantages than legacy light sources. First, LEDs can directly convert the electrical energy to light rather than producing lots of heat by a superheated filament, ionized gas, or arc discharge. So they can save up to 90% energy compared to a legacy bulb with the same light output. Besides, the mean time to failure (MTTF) of LED can be up to 10 times longer than that of legacy light sources (see Table 1-1), avoiding the hassle of frequent changing of light bulbs. This significantly reduces waste but also saves money in the long term. Besides, various color and color temperatures from 2700 to 12,000K are available, as well as saturated colors. They are solid-state devices, which are much more robust than any glass envelope lamp and contain no hazardous materials like fluorescent lamps.

(a)

(b)

Figure 1-16 Artificial light sources: legacy light sources (a) and low and high power LEDs (b)

Table 1-1 Key characteristic comparison of different light sources

Name	Optical spectrum	Efficacy (lm/W)	Lifetime (MTTF) (hours)	Color temperature (kelvin)	Dominant color	Color rendering index
Incandescent	Continuous	4–17	750-2000	2400–3400	Warm white (yellowish)	100
Halogen	Continuous	16–23	3000–4000	3200	Warm white (yellowish)	100
Fluorescent	Line spectrum Mercury +Phosphor	52–100 (white)	8000-20000	2700–5000	White (various color temperatures), as well as saturated colors available	15–85
Metal halide	Quasi-continuous	50–115	6000-20000	3000–4500	Ditto	65–93

Sulfur lamp	Continuous	80–110	15000-20000	6000	Pale green	79
High pressure sodium	Broadband (Pressure dependent)	55–140	10000-40000	1800–2200	Pinkish orange	0–70
Low pressure sodium	Narrow line	100–200	18000-20000	1800	Yellow, no color rendering	0
LED	Die(s) emission and phosphor (for white LED only)	Up to 300 (Cree)	35,000–100,000	Various white from 2700 to 12000	Various color temperatures, as well as saturated colors	Up to 95 (white)
OLED	Broadband (RGB for white)	54-124	30,000–100,000	Various white from 2300 to 9700	Ditto	74-90 (white)
Electrodeless	Mercury line +Phosphor	70–90 (white)	80,000–100,000	Various white from 2700 to 6000	Ditto	70–85 (white)

Note: CRI definition is not always valid for LED technologies.

1.3.2 Artificial light and plants

Plant Artificial Radiation Sources (PARS), also called greenhouse light or grow light, is a kind of supplemental light or full light to promote photosynthesis of plants. The history of plant cultivation by electric light has been over 150 years. Like the history of artificial lighting, PARS has undergone four stages: incandescent lighting, open arc lighting, enclosed gaseous discharge and solid-state lighting. Now PARS has been widely used in greenhouse and plant factory [67].

The lack of illumination time, insufficient light intensity and light quality are the common phenomenon for traditional glasshouse and other similar facilities. Due to changes of seasons and weather conditions (overcast, rain, snow, fog, haze, etc.), in addition to air pollution, drifting and other negative factors, there is insufficient sun light in greenhouse. This causes serious reduction of output even crop failures. Besides, the sunlight into greenhouse reduced by 20%-50% because of the greenhouse structure and the block of films. Low light intensity seriously affects the yield and quality of horticulture. Therefore, only using sunlight cannot get enough photosynthesis to meet the needs of crop growth and quality. Supplemental lights are urgently needed for photoperiod control for the plants in different regions [41]. PARS is essential for artificial light cultivation. Precision intelligent light environment regulation is a fundamental determinant for plant tissue culture, plant factories and edible fungus factory under artificial light.

1.3.2.1 Legacy light in CEA

Legacy light sources in CEA include incandescent lamp, fluorescent lamp, high pressure sodium lamp and metal halide lamp, especially fluorescent and high pressure sodium lamps have been the most widely used PARS until now (Figure 1-17). However, most legacy PARS cannot be fully competent due to their characteristics and limitations.

First, the low electrical efficiency and large power consumption. The light energy costs account for about 60% -70% of the total electricity costs. It is mainly manifested by the low electro-optical conversion efficiency, such as high pressure sodium (HPS) lamp only 30%, fluorescent lamp 40%. Most of the energy is released as heat, thereby resulting in temperature rises, and increasing consumption of energy cooling system (air cooling or air conditioning systems).

Second, less effective spectral power distribution (SPD). The SPD of legacy light is relatively fixed and different to adjust. It has much invalid or inefficient wavelengths, which cannot perfectly match selective absorption spectrum of plants.

Third, large radiant heat. The legacy lights emit lots of infrared spectra, which spread in the form of heat. For example, the temperature of high pressure sodium lamp can reach 200 ℃, so when this kind of light is close to plant leaves, it is sure to burn the plants, causing plants dysplasia and even death. So legacy lights cannot illuminate the plants in a short distance.

(a) (b)

Figure 1-17 Fluorescent based PARS (a) and HPS based PARS (b)

1.3.2.2 LED light in CEA

LED is a kind of solid-state lighting; its applications in protected horticultural is one of the greatest advances over the past few decades; its wide applications have landmark significance [41]. In 2013, according to industry analyst of Wintergreen Research, the output of world LED lamps for plant factory was up to $ 1.2 billion, a 27% increase over 2012. The developmental stages of LED lighting in CEA is shown in Table 1-2.

Table 1-2 Develpmental stages of LED lighting in CEA [68]

Year	Key events
1989-1990	Red LED (660nm) was first used for plant production

1993	LED was used for plant growth in outer space
1994-1995	LED was used in plant research instrumentation
1995-1996	High output blue LED was invented NASA used LED in outer space for plant production
1999-2000	High power LED (1 W) was available The first commercial plant production by LEDs was carried out in Japan
2000-2001	Commercial LED driver module was developed
2001-2002	High bright LED array with multi-spectra was developed
2003	LED indoor grow light was commercially available
2004	LED was used in the plant canopy
2004-2005	High power units (>1W) were developed
2005-2006	Large scale LED array
2006	High efficiency and performance LED Greenhouse supplemental lighting by LED
2008-2013	Red and blue LED became the main grow lighting Various LED devices were applied in protected horticulture

LED is a kind of sustainable lighting and an ideal alternative for plant growth. It can directly convert electrical energy into light energy. According to the latest report, LED has a remarkable energy-saving effect. The electro-optical conversion efficiency can reach up to 60%, much better than HPS lamp: 30%, fluorescent lamp: 40%. LED can be powered by flexible DC power supply. It can easily realize intelligent control of light quality, intensity and photoperiod, which is very difficult to realize for legacy light sources. Due to its optical characteristics and spectral advantages, LED light source cannot be matched by legacy source in plant production. LED is an ideal source for agricultural production. The advantages of LED grow light are mainly reflected in the following points:

A. LED grow light is more efficient than legacy light. The SPD of LED can be customized and adjusted acoording to the selective absorption spectrum of plants;
B. LED as a cold light source can illuminate close to the plants, which improves space utilization;
C. LED uses DC power, so it can be easily controlled and adjusted for optimal light intensity, quality and photoperiod, suitable for large scale and industrial production;
D. Its own advantages such as small size, light weight, solid material, monochromatic light, energy saving, long life, environmental friendly, durability, safe, etc.
E. LED light source device has many varieties (light board, strip light, light tube and light bulb), which is suitable for protected horticulture in various fields;
F. LED light source is an effective tool to study photobiology. Monochromatic LED test system can reveal the biological characteristics as the foundation of LED applications in plant factories.

Energy consumption as the main operating costs is an important reason for the high cost of running plant factories. Therefore, reducing energy consumption of the lighting system has become the main way for energy saving. Taking plant factory as an example, the lighting system is the largest energy consumption, accounting for more than 60%; air conditioning system is the second one, accounting for more than 30%. Although LEDs have many advantages, LED light system for plant growth should be designed properly to get the best performance and lifetime. LEDs do not radiate heat directly, but do produce heat, so heat sink should be used to dissipate the heat. Last but not least, because LEDs are directional light sources, external optics are necessary to create the desired spectral power distribution [56].

Table 1-3 Comparison of different lamps in CEA

Comparison	Incandescent	HID	Fluorescent	LED
Power efficiency	5%	30%	40%	60%
Utilization of radiation	low	low	low	high
Lifetime	low	medium	medium	high
Heat productivity	high	high	low	low
Spectrum Adjustment	no	no	no	yes
Price	low	medium	medium	high
As PARS	elimination	widely used	widely used	the ideal

Currently plant factory used LED technology is mainly mastered by a few developed countries, such as Japan and Netherlands. The spread and application of LED in protected horticulture exist the following obstructions [44, 69].

A. Plant growing development and nutrient absorption have the properties of diversity and complexity.
B. The domain of agricultural production is complex, and biomorphic forms have various shapes, so different light environment is needed in different space and growth phases.
C. There are a number of combinations among light quality, intensity, photoperiod and light/dark cycle, each of which needs to be examined for its biological effects.

D. There is less cooperation between LED lighting company and agricultural research center, corresponding less research investment.
E. Although the LED lighting technology for agriculture is developing very fast, the process of commercialization of intellectual property is very slow.
F. LED lighting products and control device have relatively high prices, which becomes an obstacle to practical application.
G. The most important point: microscopic mechanism of photobiology is not clear enough, causing questions to the application potential and reliability, and slowdown the pace of application promotion.

1.3.2.3 Light Environment for plant growth

1.3.2.3.a Introduction

Photosynthesis is the most fundamental and important chemical reaction in the world, without that all life on Earth will disappear. The chemical reaction is shown in equation (1).. It is deeply affected by the environmental factors. In the final analysis, all the factors controlled in CEA (ventilation, heating, thermal screens or shade, humidification, recirculating) are to promote the photosynthesis.

$$CO_2 + 2H_2O + Photos \rightarrow [CH_2O] + O_2 + H_2O \quad (1).$$

Light is an essential part of the reaction. It plays a critical role and has a direct effect on photosynthesis. Light control strategy has a profound significance for the development of protected horticulture.

Based on the analysis of the previous sections, The spectra offered by fluorescent or HID lamps cannot be adjusted specifically for plant growth. Typically a mass of wavelengths is emitted, yet very few of those wavelengths truly benefit the plant's photosynthetic rate. LED light source is the ideal choice of plant production and has the potencial to produce the most photosynthetically efficient light [70]. So we mainly talk about control strategy for LED light. Properly configured horticulture LED light systems provide plants with the optimal light treatment they need and therefore get the best growth and best production.

For greenhouse, the light transmittance is a basic evaluation index. Transmittance of greenhouse is the ratio between the amount of incident light before and after into the greenhouse, which is influenced by transmission properties of covering material and the rate of skeleton shadow. With the different angles of solar radiation in different seasons, greenhouse transmittance is subject to change. In general, the transmittance for multi-span plastic greenhouse is 50% to 60%, for the glass greenhouse it is 60% to 70%, for solar greenhouse it can reach more than 70%. For energy-saving solar greenhouse it is generally 60% to 80%. The greenhouse transmittance becomes a direct impact factor on crop growth and selecting the plant species. when the light is insufficient, supplemental light should be used to extend the exposure time. The light intensity can be adjusted automatically according to real time light intensity, and suitable for plant growth.

For plant factory, all the light environment is created by artificial light sources, so in addition to the control of light quality, quantity and photoperiod, the plant needs at different stages should also be considered. Intelligent control systems of light environment comprise of LED light sources, sensors, computer, etc. Related adjustment should be performed to get the best light environment. Finally realize three objectives: low energy consumption (energy efficient), good quality and high yield.

1.3.2.3.b LED based photobiology

Photobiology is the study of the relationship between light and biology (animals, plants, microorganisms). It is multidisciplinary field including biology, chemistry and physics. It aims to clarify how the light information affects organisms, as well as the mechanism of biological reaction to light. LED based photobiology research is the basis of light regulation and a multi-discipline crossed new area. The narrow spectrum of LED has the potential to clarify the relationship between plant varieties, light environment characteristics, photomorphogenesis, physiology, biochemistry and molecular biology. It can provide scientific basis for LED lighting design and light environment regulation. Plants need to be focused on the individual study from multi-angle. Particularly in the LED light quality and plant photosynthetic physiology, plant nutrition, and plant metabolic physiology. There are many issues should be discussed and clarified in plant molecular biology [42].

Figure 1-18 shows the general spectra of sunlight, LED, incandescent, flourescent and HPS lamps. Compared with the selective spectrum of plant pigments, only LED can provide more efficent spectrum in the blue and red range. The combination of LED spectra has the potencial to produce the optimal spetrum for specific species.

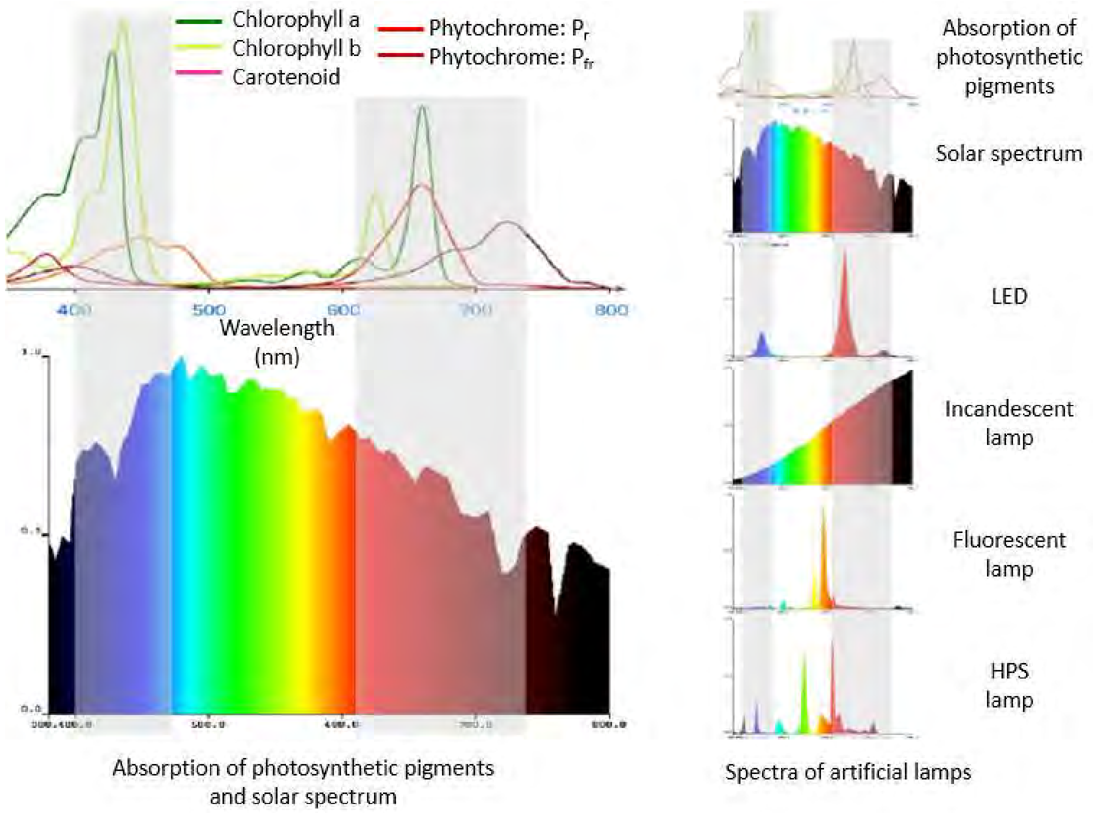


Figure 1-18 Absorption spectrum of plant pigments compared with the spectrum of sunlight, LED, incandescent, fluorescent and HPS lamps [71]

Lighting recipe (LR) and light environment control strategy (LECS) is the precondition to get the maximum energy efficiency under the premise of high yield and quality. With high yield and quality as the goal, LR refers to a parameter set that contains all the light information database (light quality, quantity, photoperiod, etc.) for the growth and development of particular plant species in different growth stages. Light quality in LR contains visible light quality, UV and far-red light, of which blue and red light are essential for plant production, and the others are beneficial light. LR is the basis for intelligent control of light sources and light environment, the establishment of LR database has great significance in plant factories with artificial (or electric) lighting (PFAL). LECS is a method to direct control and switch the light environmental parameters through the computer based on LR in different growth stages [41].

1.3.2.3.c Spectra for plant growth

The plant requirement of light quality has reached a consensus: essential light quality is not continuous but selective. Red and blue light are the essential light that have higher relative quantum efficiency of photosynthesis, and they can fulfill normal growth and development of plants. Adding certain amount of blue light to the red is helpful to photosynthesis and absorbtion of mineral nutrition. For the other spectra, they are difined as beneficial light, but they cannot independently complete the life cycle of plants. Red and blue LED combinations can replace the fluorescent spectrum of continuous cultivation, it laid the foundation to the red and blue LED light cultivation. It simplifies light quality from continuous spectrum to red and blue combinations. This provides a theoretical basis for horticulture with LED, also greatly reduces the manufacturing cost of the lamps. In the aspect of light quality, the studies reported ultraviolet to far-red light, especially red, blue, and their combinations. The results often concern the yield, quality, growth and physiological and biochemical processes. Studies show that in the visible spectral range 380-760nm, the light energy for plant photosynthesis accounts for 60%-65% of physiological radiation energy. The peak absorption wavelength is mainly 610-720nm of red-orange light and 400-510nm of blue-violet light. Sometimes, duty cycle of 25% -50% can accelerate plant growth. Polychromatic light is more suitable than chromatic light for plant growth [42].

Light quality and control strategy is the precondition to maximize utilization of light energy, meanwhile it is also an effective way to reduce energy consumption. A great light environment can reduce growing cycle, enhance production and improve quality. Well-designed agricultural LED lighting specifications can promote agricultural industrialization and standardization.

1.4 Plant selected in this study

In general, cultivation of higher plants has more requirements for the experimental space, test instruments, LED lighting system (system size and number of LED), etc. Moreover, the growing cycle is relatively long and most of the time not compatible with duration of Ph.D. Thesis.

Thus, at the beginning we started with a general study not focused on one particular plant, but based on relative quantum efficiency (RQE) curve representing the required spectrum for “generic” plants (RQE curve is based on the CO_2 fixation rates of 22 different plants). Then, in a second step we focused on a particular plant: *spirulina platensis*. This work was supported by the program EPICURE found by Region Midi-Pyrénées and European FEDER.

Therefore, our study for plant growth is split in two parts:

1) Study on generic plant systems based on RQE curve (Chapter 4);
2) Study on a particular plant: *spirulina platensis* (Chapter 5).

The main commercial large-scale culture of microalgae started in the early 1960s in Japan with the culture of Chlorella, followed by *spirulina* in the early 1970s at Lake Texcoco, Mexico. *Spirulina* is produced in at least 22 countries: Benin, Brazil, Burkina Faso, Chad, Chile, China, Costa Rica, Côte d'Ivoire, Cuba, Ecuador, France, India, Madagascar, Mexico, Myanmar, Peru, Israel, Spain, Thailand, Togo, United States of America and Viet Nam [72].

Spirulina cultivation can be achieved in two ways: open ponds and photobioreactors. The former is badly affected by the deteriorating environment, so the latter is gradually developing. Nowadays, the industrial production of *spirulina* by LED lighting system are seldom reported, but the scientific researches were carried out in the laboratory [73-76]. However, the combined application of different LEDs has seldom been studied, especially for LEDs emitting between 500 and 630nm or above 700nm (far-red region); a relative dearth of studies on red-to-blue ratios for *spirulina* means that no final conclusion is possible [61].

S*pirulina platensis* is a special plant. It has some similar pigments with photosynthesizing plants such as chlorophyll, carotenoids, etc. The chemical reaction mechanism of photosynthesis is also the same. Recently, *spirulina platensis* exhibits a strong interest and gets more attention. Many authors did research on it with PARS because of its nutritional and medicinal properties [61, 74, 75, 77, 78]. More important for this study, it has a much shorter growth cycle compared with average plants. Its metabolites are more simple than higher plants. Thus, we chose *S. platensis* as the experimental subject. The optimization of LED spectra is mainly on this alga.

1.5 Conclusion

In this chapter, we introduced legacy and modern light sources and the lighting systems. Most of the lighting systems have drawbacks for plant growth, but the applications of LED have unparalleled advantages in controlled environment agriculture. Thus, first step we chose LED light sources and optimize the lighting system on a “generic” plant and in a second step on *spirulina platensis*.

Chapter 2
LED Characteristics: Experimental Setup & Measurements

Synopsis

Experimental setup was built based on a home-made temperature control box and light measurement system of integrating sphere. The electrical, thermal, optical and colorimetric characteristics of LEDs were measured and analyzed. LED behaviors were described by electrical, PAR and spectral models.

2.1 Experimental setup

2.1.1 Junction temperature measurement based on temperature control box

Semiconductor is very susceptible to high junction temperature (T_j), which can lead to early failure and influence the performance. So T_j is a key parameter of LED to test. Traditional method is to put a temperature sensor very close to the semiconductor junction and test the output temperature. However, this method has physical limitations because of the finite size of the sensor; additional error would lessen the accuracy of the test results [79]. There are also some other methods to test T_j, such as thermal camera, optimal test methods (OTMs) $P_{opt} = f(T_j)$, wavelength shift method (WSM) $\lambda = f(T_j)$, electrical test methods (ETMs), and the ratio of white and blue spectral component [80-82]. But there are always some drawbacks like inaccuracy, so an improved method should be used to test T_j.

Normally LEDs' T_j and V_f have a linear relationship up to 100 ℃. The relationship can be described as equation $T_j = aV_f + b$ [83, 84]. What we need is to design experiment and get the constants a and b.

A specific temperature control box was designed to find the relationship between T_j and V_f. The materials related to a metal box (40*30*20cm), 2*200W heating resistors (PTC Conductive Heating Elements), a temperature controller (CB100-FK07), an electric fan (180 m^3/h), thermal insulating sheet (Thermal Conductivity: 0.04 W/mK) and one bottle of black painting. The basic structure is shown in Figure 2-1. The box can create a uniform temperature environment, and the temperature can be adjusted from the room temperature to 80℃. We put the LEDs in the box and stepped up the temperature with about 10 ℃ interval. Each time when the box reached to thermal equilibrium (as well as T_j of LED), the source meter (keithley 2602A) gave a 10 mA pulse current with a very short duty cycle, which could avoid extra heat by LED junction. So the accurate V_f was easily obtained.

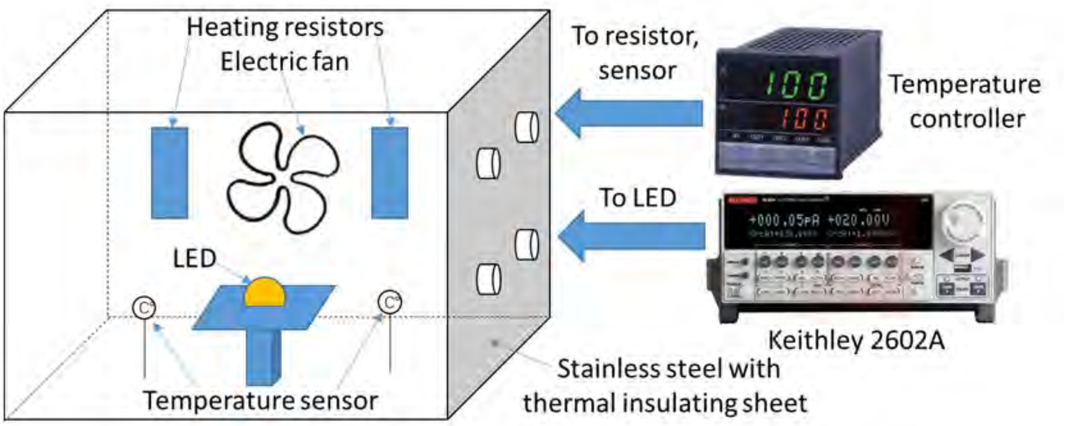


Figure 2-1 The basic structure of the temperature control box

2.1.2 Light measurement system for LEDs characteristics

Figure 2-2 shows the measurement system for LEDs' electrical, thermal, spectral and colorimetric characteristics. It includes integrating sphere (diameter 25cm), spectroradiometer (Specbos 1201), source meter (keithley 2602A), computer and testing software, and a small temperature control system including temperature sensor and controller, heating resistor with thermal insulation and a heat sink (Figure 2-3). The function of an integrating sphere is to spatially integrate radiant flux. Specbos was used to test the spectral power distribution and quantity. Keithley 2602A can provide accurate currents to drive LEDs and test V_f with a 10 mA pulse current. The PC software included JETI LiVal for specbos and a programmed software (Figure 2-4, made by Leng SOVANNARITH in Laplace) for Keithley to regulate the V_f and I_f. The small temperature control system was used to approximately increase T_j but not accurately. According to the relationship of V_f and T_j tested by the temperature box, T_j can be accurately determined.

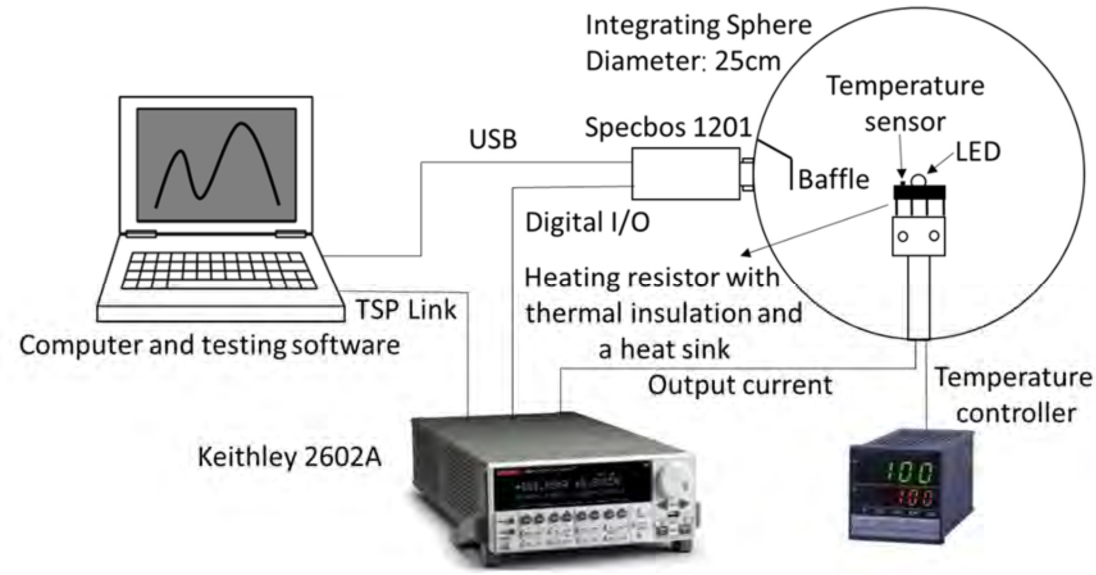


Figure 2-2 Light measurement system for LEDs' charecteristics

Figure 2-3 PC software for Specbos 1201

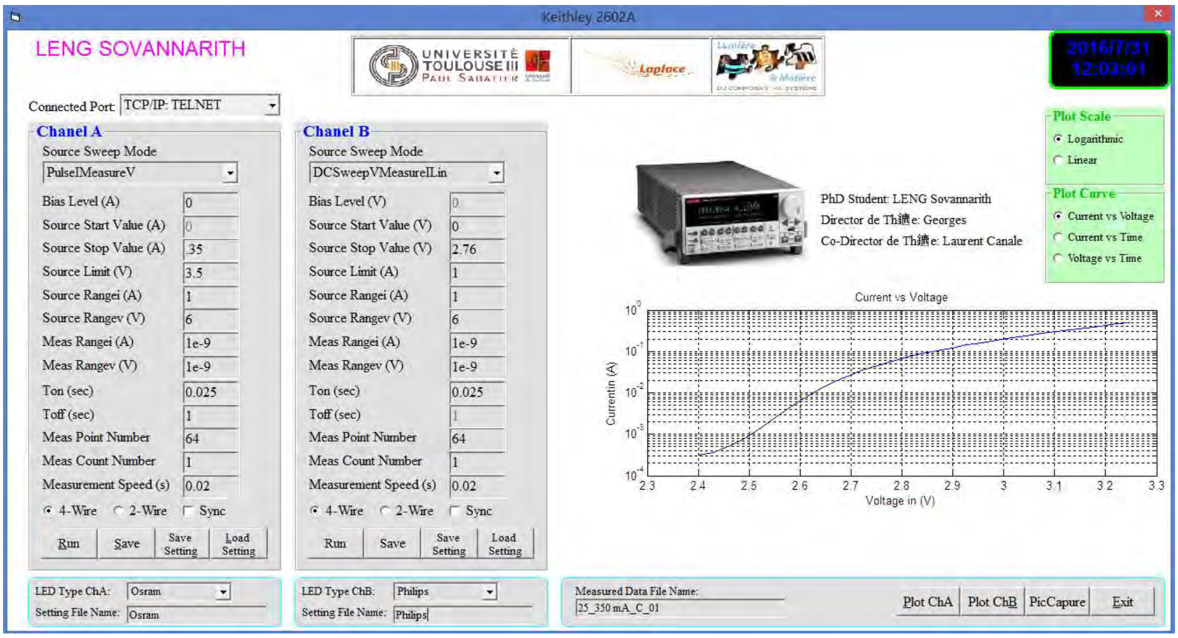


Figure 2-4 PC software for Keithley 2602A (made by S. Leng)

2.2 Measurement for LED characteristics

2.2.1 Electrical characteristics

It is necessary to consider electrical parameters before designing a LED lighting system. LED can emit light when the P-N junction is forward biased. There is a threshold voltage, above which the forward current (I_f) will pass through the LED. And after I_f will increase exponentially but a slight increase in voltage. So normally constant current is considered to drive the LED devices. Most of the case, LED is not allowed with reverse voltage or current, which could totally damage the LED. Low power LEDs often have a typical current of 20 mA and less than 1 W; high power LEDs often have a typical current of 350 mA and more than 1 W. There are two main ways to control the current of LEDs: analog control and pulsed width modulation (PWM). Although PWM control has lower efficiency than analog control, it is better for driving uniform LEDs with the same color and forward voltages [62].

The most used electrical characteristic is the V-I characteristic. Five LED colors were measured in Figure 2-5. The threshold voltage depends on the material used. The typical current for red and amber is 400 milliampere (mA); for green, blue and white, it is 350 mA. The surge current for all is 2-2.5 A.

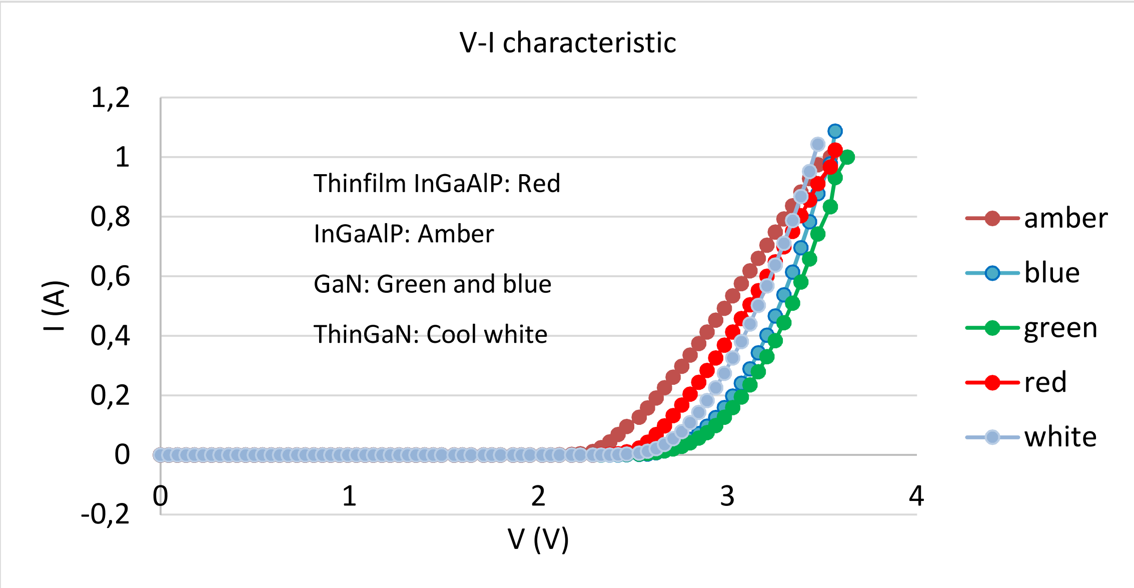


Figure 2-5 V-I characteristic for five LED colors

Besides, four red LEDs of the same type were tested in the same condition. There are small differences for I-V characteristic (Figure 2-6). That is because semiconductor materials and doping in LED are not completely uniform in the production process.

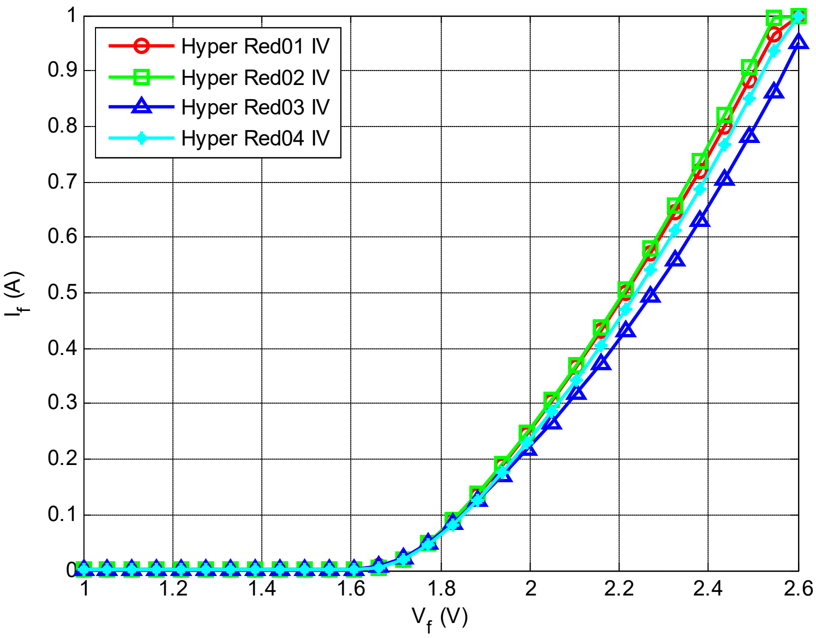


Figure 2-6 I-V differences between 4 same hyper red LEDs

Two measurements were adopted by changing the excitation source for one hyper red LED. One was pulsing I_f to measure V_f (PulsedIMeasureV) and the other was pulsing V_f to measure I_f (PulsedVMeasureI). The test I-V curves kept consistent (Figure 2-7), which means that I-V characteristics are not affected much by the form of excitation source.

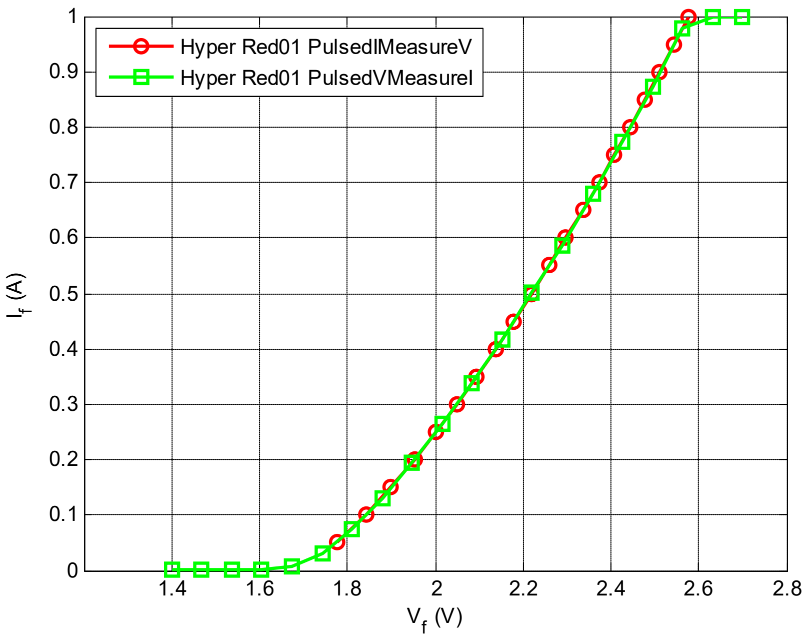


Figure 2-7 I-V characteristic by two excitation sources: PulsedIMeasureV and PulsedVMeasureI

2.2.2 Thermal characteristics

Junction temperature (T_j) is a critical parameter of LEDs. It can influence the other parameters such as V_f, peak wavelength, spectral width, luminous efficacy, etc. In order to guarantee a longer lifetime of LEDs, thermal management is necessary.

In this part the experimental setup was only used to determine T_j. Using the temperature control box, we tested 4 red LEDs. In order to reduce the influence of forward current (producing extra heat), a small pulse current 10 mA with a 0.1% duty cycle was used to measure the V_f. When the environmental temperature in the box was stable, we made the measurement. The results are shown in Figure 2-8 and the following equations. There is a linear relationship between T_j and V_f. V_f is decreasing with the junction temperature increasing. With this method, it will be easy to measure the optical properties under certain T_j.

$$T_{j01} = -776.9V_{f01} + 1334\ (R^2 = 0.9999)$$
$$T_{j02} = -778.1V_{f02} + 1336\ (R^2 = 0.9998)$$
$$T_{j03} = -787.2V_{f03} + 1339\ (R^2 = 0.9998)$$
$$T_{j04} = -778.0V_{f04} + 1339\ (R^2 = 0.9999)$$

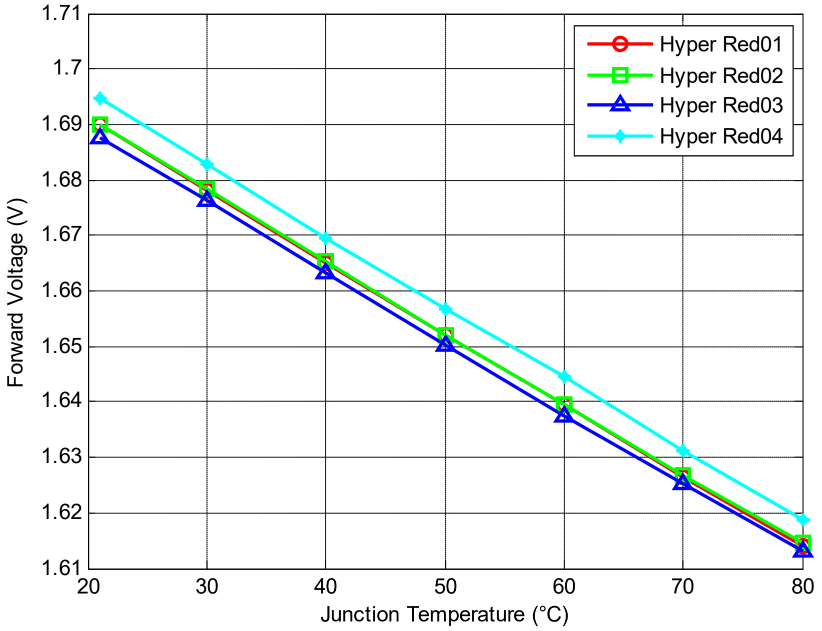


Figure 2-8 Junction temperature (℃) vs Forward voltage of four hyper red LEDs

2.2.3 Spectral characteristics

Spectral power distribution (SPD) is a crucial parameter of optical property, which determines the other radiometric or photometric quantity such as photosynthetically active radiation (PAR), radiant flux, radiant intensity, irradiance, radiance, luminous flux, luminous intensity, illuminance, luminance, etc. SPD describes the power per unit area per unit wavelength of an illumination, but it is greatly affected by T_j and forward current (I_f). Figure 2-9 shows the SPD of five GOLDEN DRAGON LEDs at nominal currents.

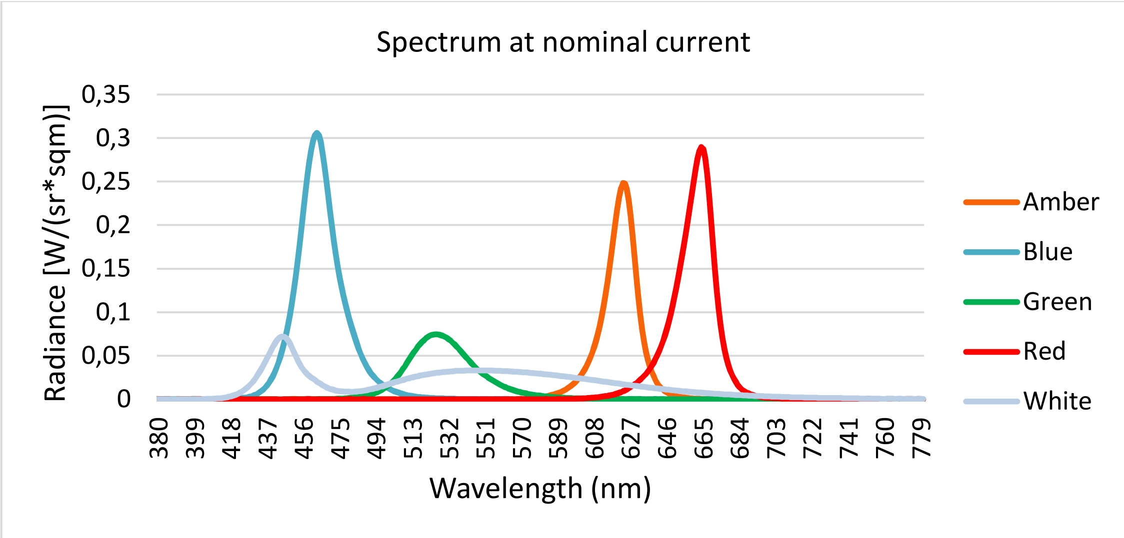


Figure 2-9 Spectral power distribution for five GOLDEN DRAGON LEDs at nominal currents

Figure 2-10 shows the SPD of a hyper red LED at different I_f (0.05 to 1A with a 0.05A interval) at room temperature. From the spectra, an obvious red shift is appeared. Besides, the current dependence of peak wavelength at the room temperature is shown in Figure 2-11. Because the resolution of Specbos is limited, the points fit was made. It indicates totally 5nm difference from 0.05-1A, which means about 0.25nm red shift for each interval. We also tested the temperature dependence of peak wavelength for the hyper red LED when I_f = 0.3A (Figure 2-12). There is also a red shift, totally about 12nm from 21℃ to 84℃, about 1.9nm red shift for 10℃.

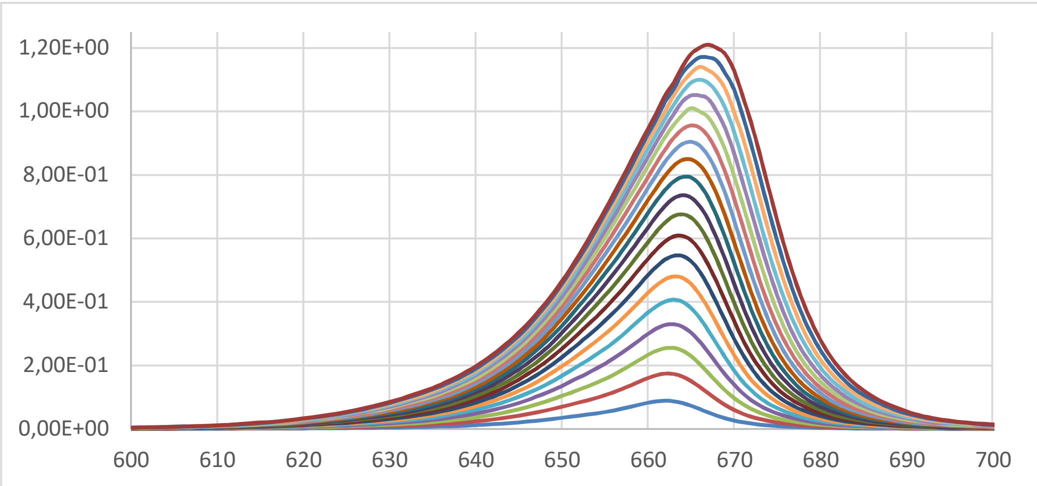


Figure 2-10 SPD of a hyper red LED at different I_f (0.05-1A) at room temperature

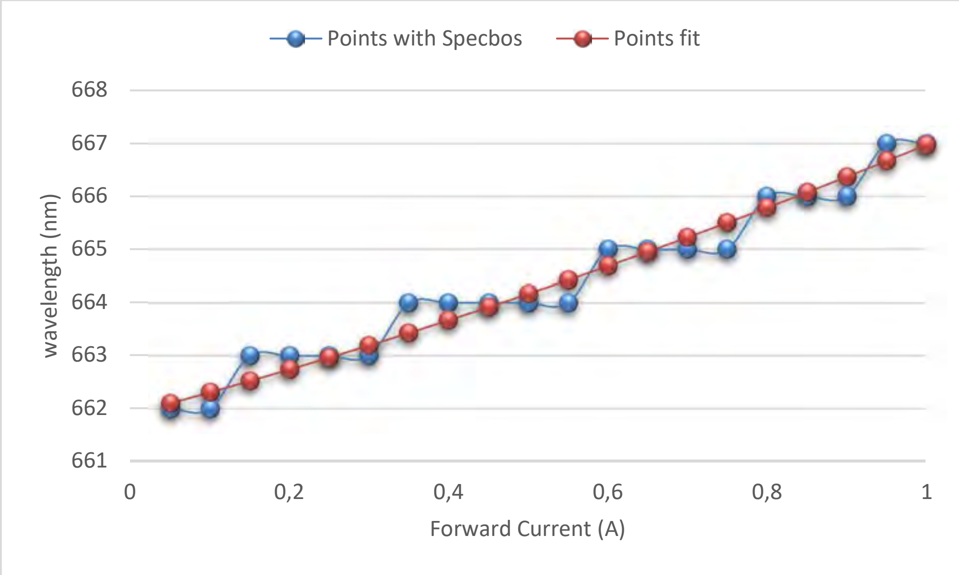


Figure 2-11 Current dependence of peak wavelength for a hyper red LED at the room temperature

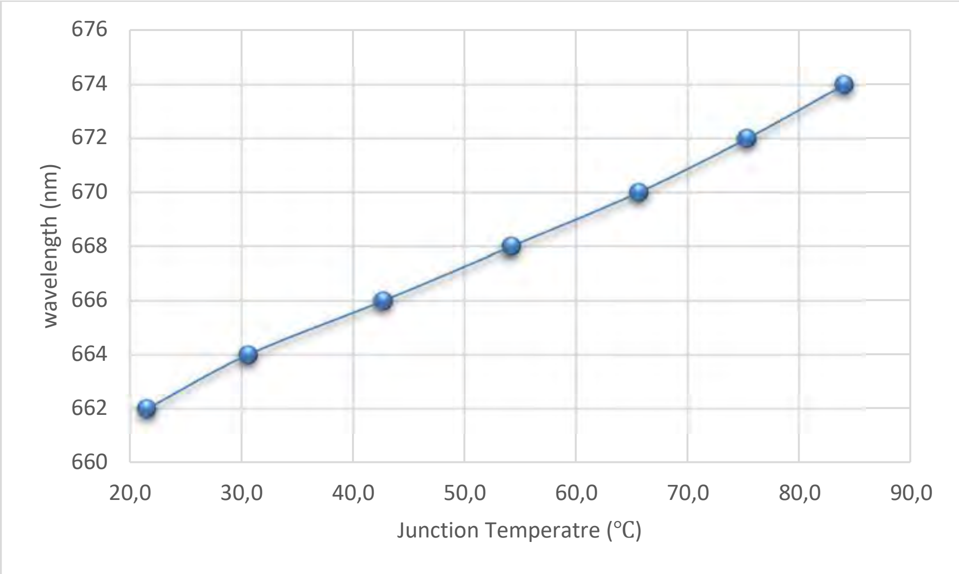


Figure 2-12 Temperature dependence of peak wavelength for a hyper red LED when I_f= 0.3A

When the T_j and I_f increase, the luminous flux (Φ_v) and PAR (Φ_p) both increase, but the efficiency decreases. Different I_f (0.05-1A) and T_j (21-84℃) were used to test the luminous flux and PAR of a hyper red LED. From Figure 2-13 and Figure 2-14 we can see that the luminous flux is influenced more by I_f and T_j. Relative luminous flux Φ_v/Φ_v (350mA) is less than 2.5 at 1A compared with 2.7 of relative PAR Φ_p /Φ_p (350mA). In fact, the relative PAR almost presents a linear function, but the relative luminous flux presents like a quadratic function. Relative luminous flux Φ_v/Φ_v (21℃) is less than 0.7 at T_j = 84℃ compared with more than 0.9 of relative PAR Φ_p /Φ_p(21℃). Both of the curves present a linear function. Another conclusion is that the temperature T_j influenced more seriously than I_f.

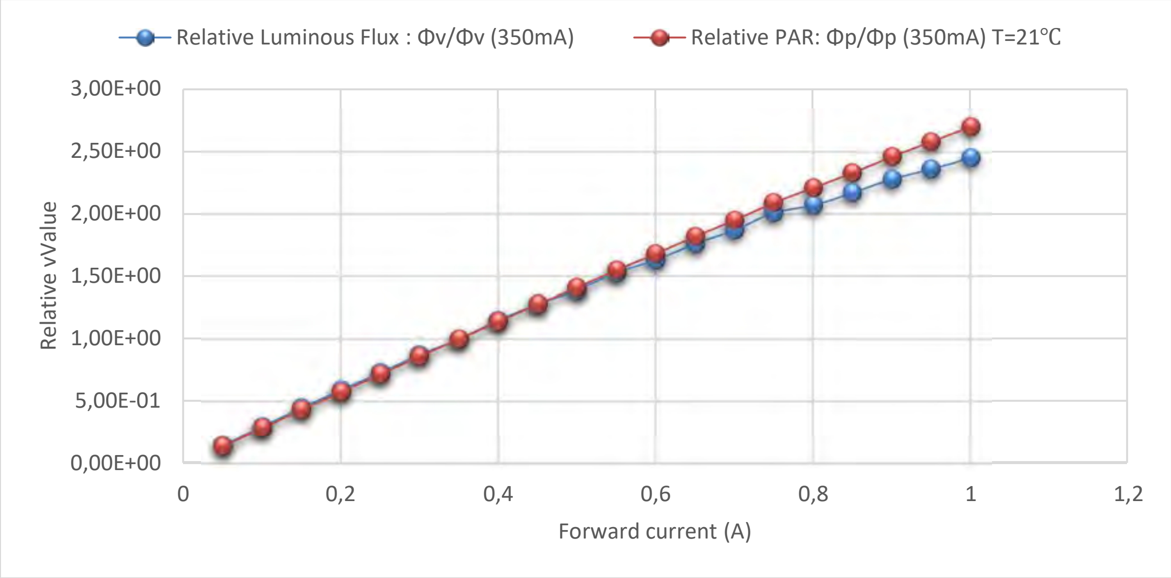


Figure 2-13 Forward current dependence of hyper red LED for luminous flux and PAR.

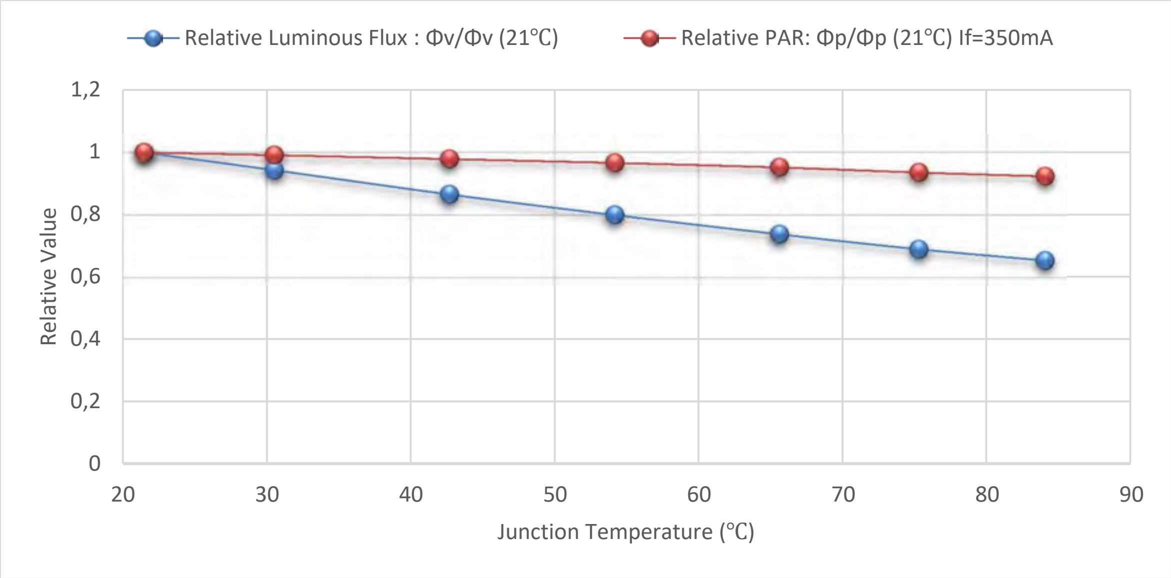


Figure 2-14 Temperature dependence of hyper red LED for luminous flux and PAR.

2.2.4 Colorimetric characteristics

Chromaticity coordinates of x, y, and z are a ratio of the red, green, and blue stimulation of light compared to the total amount of the red, green, and blue stimulation. The sum of the RGB values (x + y + z) is equal to 1. LEDs have a wide range of color temperatures (2700 – 12,000 K). Each LED color can be represented by unique x–y coordinates according to CIE (Commission Internationale De L'eclairage (International Commission on Illumination)). The color temperatures and the Planckian locus (black body curve) show how they relate to the chromaticity coordinates. The color temperature of light is equal to the surface temperature of an ideal blackbody radiator in Kelvin heated by thermal radiation. When the black body radiator is heated to high temperatures, the heated black body emits colors starting at red and progressing through orange, yellow, white, and finally to bluish white [62].

LEDs are classified into two types by color output: white LEDs and RGB LEDs. White LED packages can use red/green/blue/orange/yellow phosphors with blue LED chips to produce white light. The phosphors comprise activators mixed with impurities at a proper position on the host lattice. The activators determine the energy level related to the light emission process, thereby determining the color of the light emitted. The color is determined by an energy gap between the ground and excitation states of the activators in a crystal structure. RGB LED packages include red LED packages, green LED packages, blue LED packages, and LED packages with multi-dies in a single package producing white light using a combination of red, green, and blue LED dies [62].

A kind of EQ-White LED was measured with the test system. The EQ-White LED is produced with a blue chip and green phosphor. Its advantage is that the green phosphor has a very low conversion loss rate and makes for a very efficient light source (typ. 151 lm/W) in combination with the blue chip. Besides, it creates an adequate chromaticity coordinates and a balanced basic spectrum. The chromaticity coordinates and Correlated Color Temperature (CCT) were tested at different I_f and T_j.

Figure 2-15 shows the results at I_f 0.1 and 1A, and T_j 21℃ and 78℃. The chromaticity points shift toward higher color temperature with the increase of I_f and T_j. When T_j was fixed at 21℃, CCT changed from 4551 at 0.1A to 4641 at 1A. When I_f was fixed at 0.3A, CCT changed from 4573 at 21℃ to 4701 at 78 ℃. The results are in agreement with the previous literature [85]. The reason could be explained by a decrease in luminous efficiency of EQ-White LED.

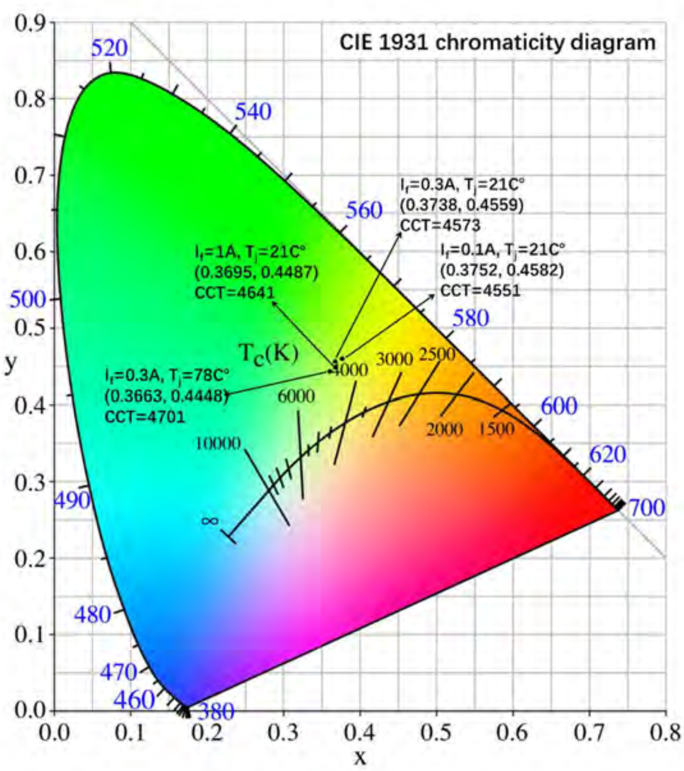


Figure 2-15 Chromaticity points of an EQ-White LED at different I_f and T_j

2.3 Modeling LED behaviors

2.3.1 Electrical model

The electrical model of LED can be assumed to be a multiple input and single output system (MISO system). The input parameters are I_f and T_j, and the output is V_f (Figure 2-16) [86]. Three-dimensional representation of the electrical model for a hyper red LED is shown in Figure 2-17. V_f slightly increases with the increase of I_f, but almost linearly decrease with the increase of T_j.

Figure 2-16 A multiple input and single output (MISO) system for LED's electrical model

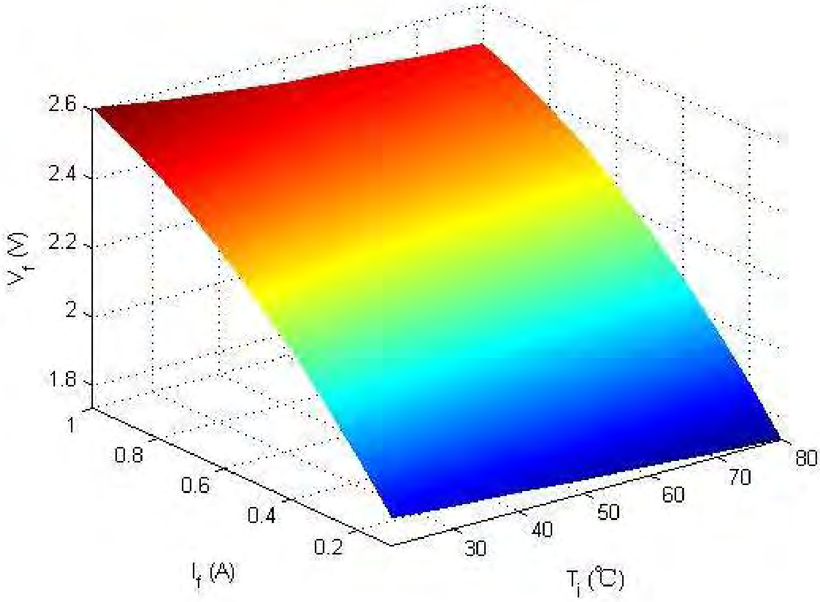


Figure 2-17 Three-dimensional representation of the electrical model for hyper red LED: the relationship between forward voltage (V_f, V) junction temperature (T_j, ℃) and forward current (I_f, A)

The custom equation of LED electrical model was created using Matlab curve fitting tool box (equation (2).). The parameters for the hyper red LED is shown in Table 2-1. V_f and T_j have a linear relationship. V_f and I_f present quadratic function relation. It will be more convenient to design LED lighting system with the electrical model.

$$V_f = aT_j + bI_f^{\,2} + cI_f + d;\ 0.05\text{A} \le I_f \le 1\text{A}, 20℃ \le T_j \le 90℃ \qquad (2).$$

Table 2-1 The parameters of electrical model for hyper red LED (with 95% confidence bounds)

Parameters	Value
a	-0.001533
b	-0.4898

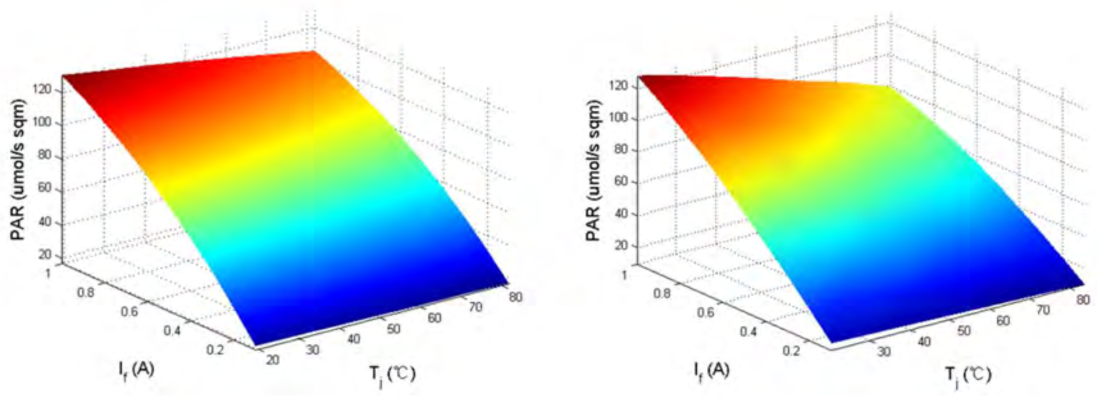
c	1.39
d	1.715
R^2	0.993

2.3.2 PAR model

According to the characteristics of LED, the forward current (I_f) and junction temperature (T_j) are two key parameters to get accurate Photosynthetically Active Radiation (PAR). PAR model can also be considered as a MISO system. The inputs are I_f and T_j, and the output is PAR (Figure 2-18).

Figure 2-18 A multiple input and single output (MISO) system for LED's PAR model

Normally, T_j and forward voltage (V_f) of LED have a linear relationship. We used 10mA pulse current produced by keithley 2602 to measure V_f at different temperatures in the temperature control (TC) box, and calculated the relationship between T_j and V_f. Then fix one LED on a small TC device and put them in the centre of integrating sphere. Use the TC device to heat the LED to reach a stable temperature; and then use 10mA calibrating current to measure V_f. Meanwhile the PAR was measured with Specbos 1201 at different current levels. Each measurement interval was five minutes in order to avoid the temperature difference of T_j. On the basis of the relationship between T_j and V_f, the true test T_j was available in the integrating sphere. Thus, the three-dimensional relationships between the PAR, T_j and I_f were obtained for a red and blue LEDs (Figure 2-19). These two kinds of LEDs were used to study the effect on the production of phycocyanin by *Spirulina platensis* in chapter 5, part 5.7.



(a) Blue LED

(b) Red LED

Figure 2-19 Three-dimensional relationship between photosynthetically active radiation (PAR) ($\mu mol \cdot m^{-2} \cdot s^{-1}$) versus junction temperature (T_j) (℃) and forward current I_f (A) of a blue (a) and red (b) LEDs

The PAR model can also be customized by equation (3).. The parameters for the red and blue LEDs are shown in Table 2-2. PAR and T_j have a linear relationship. PAR and I_f present quadratic function relation.

$$PAR = aT_j + b{I_f}^2 + cI_f + d \quad (3).$$

Table 2-2 The parameters of PAR model for red and blue LEDs (with 95% confidence bounds)

	a	b	c	d	R^2
Parameters for blue LED	-0.2227	-54.82	171.2	12.98	0.994
Parameters for red LED	-0.4078	-33.8	141.7	18.84	0.977

Through the surface fitting tool of Matlab, the fitting functions for blue and red LEDs can be more accurate, which are shown as equation (4). and (5).. The R^2 can reach up to 0.9997. However, the model function is different to interpreted. For the experiment, the accurate PAR function can be easily determined by setting I_f and tested T_j.

$$PAR_{blue} = 1.141 + 0.0071 \cdot T_j + 192.7 \cdot I_f - 0.4178 \cdot T_j \cdot I_f - 54.82 \cdot {I_f}^2 \quad (4).$$

$$PAR_{red} = -2.585 + 0.0173 \cdot T_j + 180.7 \cdot I_f - 0.7728 \cdot T_j \cdot I_f - 33.8 \cdot {I_f}^2 \quad (5).$$

$$0.05\mathrm{A} \leq I_f \leq 1\mathrm{A}, 20℃ \leq T_j \leq 90℃$$

2.3.3 Spectral model

The spectral model of LEDs can be assumed to be a multiple input and multiple output system (MIMO system). The input parameters are I_f and T_j, and the output is LED's spectrum (Figure 2-20). There are several spectral models to describe the spectrum of LEDs (Table 2-3) [86]. Gaussian function is a simple model for that and has been used in many articles, but the simulation is not the same because of asymmetric spectra of LEDs. Logistic Power Peak is considered as one accurate model for LED's spectrum, but the models are relatively cumbersome and complicated.

Figure 2-20 A multiple input and multiple output (MIMO) system for LED's spectral model

Table 2-3 Model functions for LED spectra [86]

Ord.	Name	Number of Parameters	Function $f(\lambda)$
1	Gaussian	3	$f(\lambda)=Ae^{-\left(\frac{\lambda-C}{W}\right)^2}$
2	Split Gaussian	4	$f(\lambda)=Ae^{-\left(\frac{\lambda-C}{W}\right)^2}$ with $W=W_1$, for $\lambda<C$ and $W=W_2$ otherwise
3	Sum of Gaussian	6	$f(\lambda)=A_1e^{-\left(\frac{\lambda-C_1}{W_1}\right)^2}+A_2e^{-\left(\frac{\lambda-C_2}{W_2}\right)^2}$
4	Second Order Lorentz	3	$f(\lambda)=\frac{A}{\left(1+\left(\frac{\lambda-C}{W}\right)^2\right)^2}$
5	Logistic Power Peak	4	$f(\lambda)=\frac{A}{S}\left(1+e^{\frac{\lambda-C+W\ln(S)}{W}}\right)^{\frac{-S-1}{S}}\left\{e^{\frac{\lambda-C+W\ln(S)}{W}}\right\}(S+1)^{\frac{S+1}{S}}$
6	Asymmetric Logistic Peak	4	$f(\lambda)=A\left(1+e^{\frac{\lambda-C+W\ln(S)}{W}}\right)^{-S-1}\left\{e^{\frac{\lambda-C+W\ln(S)}{W}}\right\}S^{-S}(S+1)^{S+1}$
7	Pearson VII	4	$f(\lambda)=\frac{A}{\left(1+\left(\frac{\lambda-C}{W}\right)^2\left(2^{\frac{1}{S}}-1\right)\right)^S}$
8	Split Pearson VII	6	$f(\lambda)=\frac{A}{\left(1+\left(\frac{\lambda-C}{W}\right)^2\left(2^{\frac{1}{S}}-1\right)\right)^S}$ with $W=W_1$, $S=S_1$ for $\lambda<C$, otherwise $W=W_2$, $S=S_2$
9	Asymmetric double sigmoidal	5	$f(\lambda)=\frac{A}{1+e^{-\frac{\lambda-C+\frac{W}{2}}{S_1}}}\left(1-\frac{1}{1+e^{-\frac{\lambda-C+\frac{W}{2}}{S_2}}}\right)$
10	Piecewise third order polynomial (Spline)	$4n$	Piecewise: $f(\lambda)=a_3x^3+a_2x^2+a_1x^1+a_0$, piecewise defined for n ranges $x_{k-1}\le x<x_k$, $k=1,\ \dots,n$

The single LED spectral model is shown in equation (6).. It was adopted to approximately simulate LED spectra. The relative data of simulation can be used as a reference for further optimization of LED spectrum. The LED spectrum depends on the peak amplitude A, peak wavelength λ_p (nm), and full width at half maximum λ_{FWHM} (nm).

$$S(\lambda_p,\lambda_{FWHM},\lambda)=A\cdot\exp\left(-\left(\frac{\lambda-\lambda_p}{\lambda_{FWHM}}\right)^2\right) \quad (6).$$

2.4 Conclusion

In this chapter, several LEDs were characterized with the help of a temperature control box and light measurement system. Their electrical, thermal, spectral and colorimetric characteristics have been determined. The electrical, PAR and spectral models of LED were also analyzed, from which we found junction temperature and forward current were two key parameters for the performance of LED. Too high junction temperature had a bad effect on light output and reduce the mean time to failure.

Chapter 3
Design of LED Lighting System for Plant Growth

Synopsis

In order to optimize LED spectrum for plant growth, a specific LED Lighting System (LLS) is necessary. This chapter reports the design of a home-made dynamic LLS with five channels. The objectives were to realize full spectrum (Relative quantum efficiency curve) for plants, and provide intelligent power for the following experiments. According to photosynthetically active radiation (PAR), we chose five LED colors: red, amber, green, blue and white to match the useful spectrum of plant growth. The system chart, schematic diagram and its basic functions are presented. Two operating modes of the LLS can be available, automatic and manual mode, which can flexibly change the forward current, frequency, duty cycle and period. The system can be programmed based on the characteristic of selective light absorption spectrum for certain plants. Power consumption is also reduced and finally, the LLS can dynamically adjust the light quality, quantity and photoperiod in the test conditions.

3.1 Introduction

LEDs can be powered by low-voltage DC supply. Specific wavelengths can be combined together to produce the optimal spectra according to the characteristic of selective absorption spectra for plant growth. Besides, the light intensity and period can be easily changed by analog dimmer or using pulse width modulation (PWM) method.

Compared with traditional greenhouse lighting system, LLS has been shown not only energy saving, but also advantages for dynamic, accurate and flexible spectral control. LLS and LED will be inherently ideal system and light source for greenhouse plant. Indeed, they present many advantages as a long lifetime, a monochromatic light, a cool spectrum without infrared spectrum and high light efficiency. Due to their solid structure, they are robust and thus lead to a high durability. Remarkably, a high switching frequency will not affect their luminous decay and lifespan. LED light features a narrow spectrum with small full width at half maximum (FWHM). Cool spectrum can illuminate the plant in a short distance or cross the plant canopy without burning the leaves. The luminous efficacy of white LED has increased from 5 lm/W in early 90s to about 300 lm/W in lab today, which can increase continuously with the development of new materials and configurations. Thus, greenhouses lit with light emitting diodes (LED) are becoming more and more popular.

In order to study how the light affects the different plants in growth cycle, a flexible lighting system is important and necessary. HPS and TF lighting systems are the most widely used light sources for greenhouses but not the best candidate. They produce unnecessary spectrum that leads to wasting energy. Unsuitable light environment cannot produce optimal photon flux for abundant photosynthesis. Besides, the output light is difficult to control compared with LLS. Thus, some kinds of LED lighting systems are designed with different light technologies and control strategies. These systems can produce an optimal spectrum for plant growth and require further research.

In this chapter, a specific LLS is designed for greenhouse plant. The objective is to optimize LLS for plant growth with dynamic and accurate spectrum. The design principle is described and analyzed. The design of functions and control methods are discussed in details. The test result shows the performance of the LLS system. At last, we conclude this work.

3.2 Design and analysis

There are two aspects that should be well considered. At first, the LLS has to meet the characteristic of selective spectra of plant. Secondly, it must be controlled with flexibility and produce dynamic and accurate spectrum to achieve optimal spectrum for greenhouse plant.

The radiant flux of LED is a function of the forward current and junction temperature, so constant current control and a heat sink must be adopted for the LLS. High-power LEDs are low voltage and high current-driven devices; so, matched drivers are essential to produce a constant current. A small change on forward voltage causes large change on forward current according to the diode IV characteristics. Too strong current drives to light attenuation and too small current leads to insufficient irradiation. So constant voltage control cannot guarantee the brightness consistency and affect the reliability and life time of LED.

In order to realize dynamic light for greenhouse plant, five independent channels are designed without affecting each other. Analogic and PWM dimming controls are adopted. The average output current is from 0 to 1000 mA. The maximum current is 2.5A, because a PID control strategy is used to maintain the average current constant. The working frequency can be controlled from 0 to 100 kHz. The duty cycle can be changed from 20% to 100% below 500mA of average current. The current should be set between suitable ranges according to the characteristic of the LED.

The functional block diagram for the LED lighting system is shown in Figure 3-1. It mainly includes LED unit (5 colors), power module, control module (one control box), driving module (five driving boxes) and PC software. The control box can communicate with the software and control five driving boxes. PC software as a human-machine interactive interface is designed by C# programming language. It is used to display the real time operating state of LED parameters, send commands to control box, receive the feedback of system, record and save the datum and curves. When the driving boxes receive the commands from the control box, they drive the LED array as requested. The commands include setting current (Is), frequency (f), duty cycle (D) and time sequence (T). System operating status feedback information are sent to the control box and displayed in the PC software such as the real current (Ir), voltage (Vr), power (Pr) and output threshold (O). The lighting system runs according to the commands; thus different dynamic spectra can be achieved.

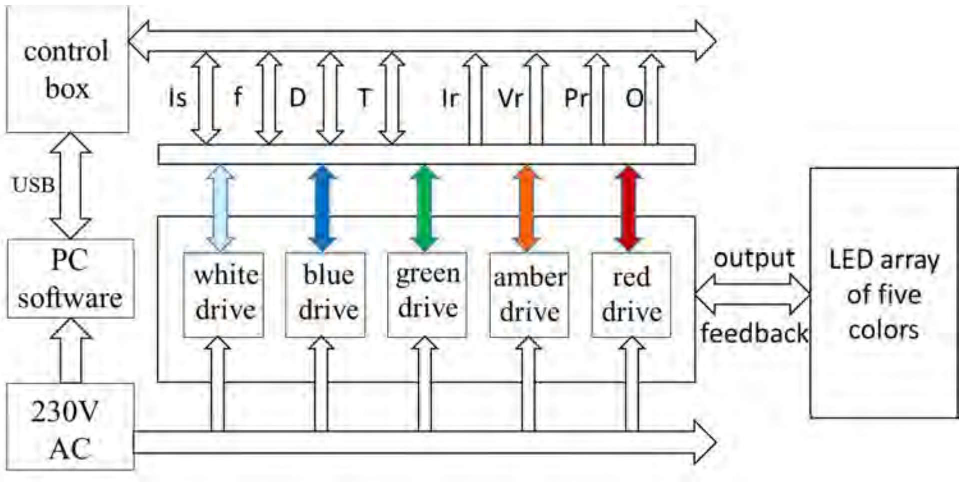


Figure 3-1 Functional block diagram for the LED lighting system

3.2.1 LED unit

According to the design principle, selective absorption spectra for plants mainly gathered between 400nm and 700nm. Thus five colors of LED are selected with the same model and configuration. For the red, amber, green and blue LEDs, the peak wavelengths are 665nm, 625nm, 528nm and 467nm, respectively. For the white color, the chromaticity coordinates are x=0.31 and y=0.32, and the color temperature is 6500K. All the LEDs have the rated power of 1 watt, maximum current 1A and viewing angle 170º at 50% current value. The LED spectrum is shown in Figure 3-2.

Two kinds of LED distribution units are designed to get the uniform illumination. Four LEDs of each color are selected. The distance of two same adjacent colors is 2r and 1.5r respectively (Figure 3-3). If we consider the basic unit as a 'pixel', then the higher the pixel is, the more uniform the spectrum is. The number of LED unit depends on the area of greenhouse plant.

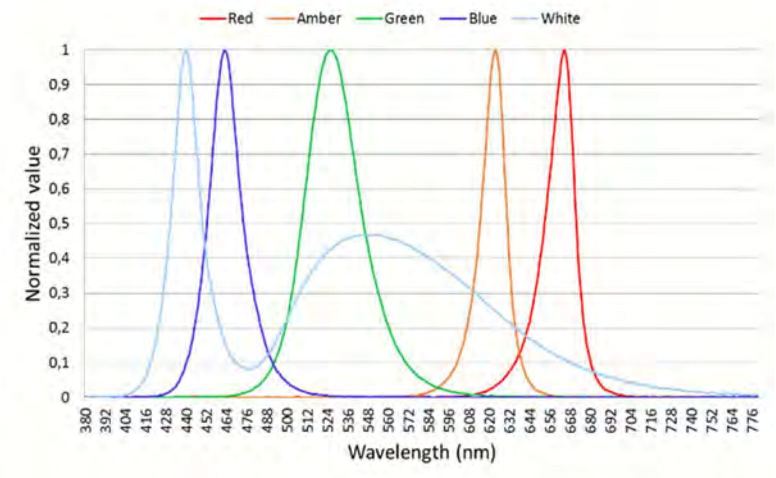


Figure 3-2 LED spectrum for five colors

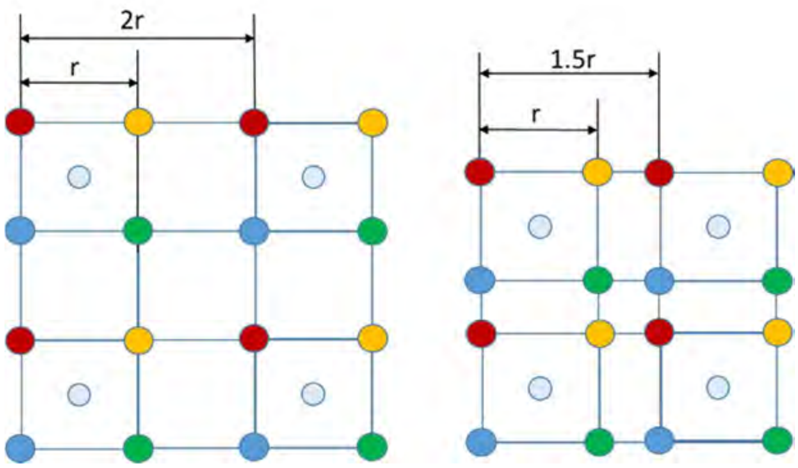


Figure 3-3 Two kinds of LED distribution unit

3.2.2 Power module

In order to provide accurate and stable current for each channel, a stable power supply is necessary. Thus, an isolated flyback circuit is used. At first, a transformer produces DC voltage in the secondary side, and then the voltage ripple is fed back to the primary side through optocoupler, thus it is self-excited and stable. Such circuits meet safety requirements identified. The output currents have relatively high precision and conversion efficiency. However, due to the need to use an optocoupler and secondary constant current control circuit, the system could be more complex with a larger volume and expensive cost. Considering the design time, we adopt 24V DC, 2.5A output as the power supply. A relay controlled by microprogrammed control unit (MUC) is used to start or close the output. The DC 24V is converted to ±12V, 5V and 3.3V to supply amplifiers, chips and MCU. The structure of the power, starting circuit and DC-DC circuits are shown in Figure 3-4, Figure 3-5 and Figure 3-6 respectively.

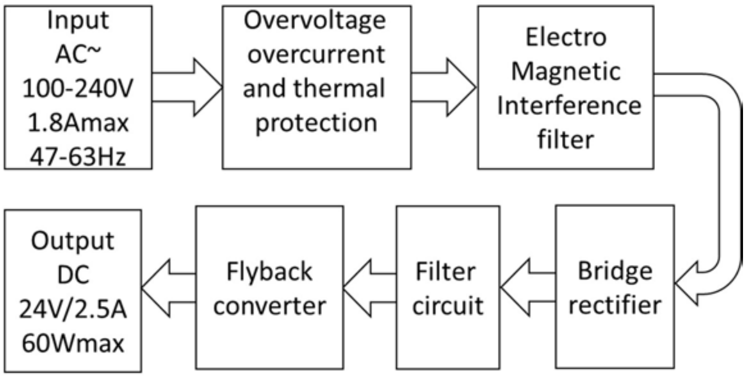


Figure 3-4 Structure of the power

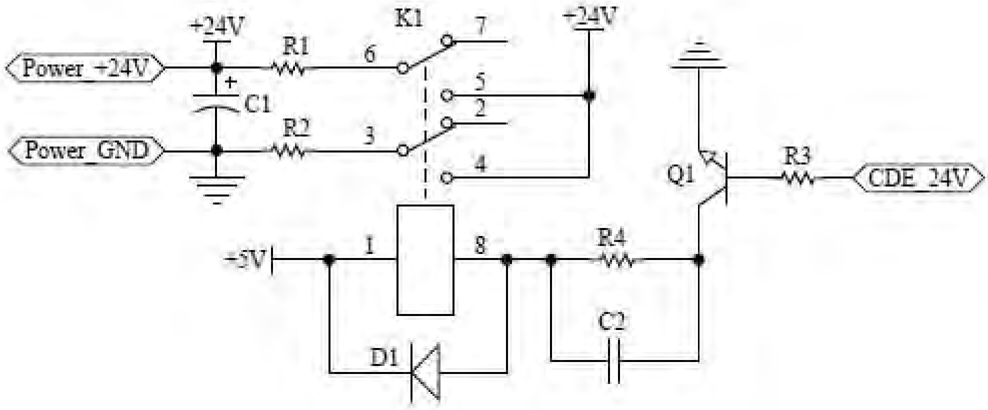


Figure 3-5 Starting circuit

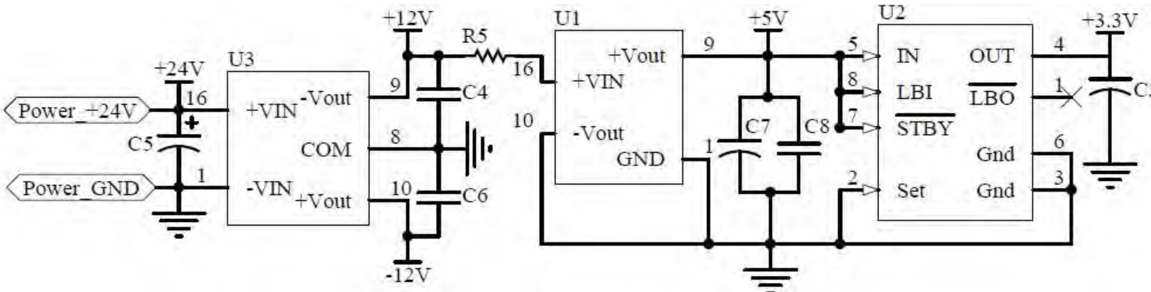


Figure 3-6 DC-DC circuit

3.2.3 Control module

This module is used to control five driving boxes and communicate with PC software. The programmable system-on-chip (PSoC) is adopted as the main control chip. Some important functions are used such as a full-speed USB, timers, I/O, interrupt controller, external oscillator, power on reset (POR), real time communication (RTC) and so on. The chip architecture boosts performance through 32-bit ARM processor core plus DMA controller and digital filter processor with an ultra-low power consumption. The simplified circuit is shown in Figure 3-7. The module is powered by USB. T1 to T5 are to send commands to five driving boxes, and R1 to R5 are to receive the feedback signals. Box_1 to Box_5 are to make sure the connections between the control box and driving boxes.

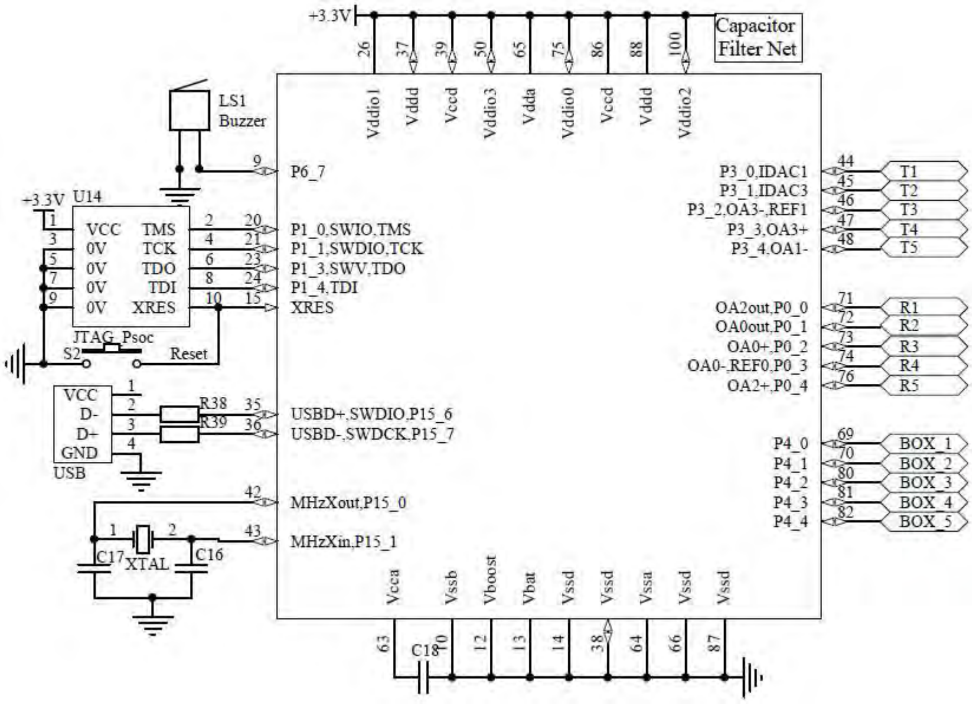


Figure 3-7 Control module schematic

3.2.4 Driving module

Driving module consists in five driving boxes. The same PSoC chip is used for each channel. It receives the commands from the control box and carries out the orders for each channel, such as the functions of regulating the output current, frequency, duty cycle, output threshold and period, detecting the forward current and voltage, sending the datum to the control box and finally displayed in the PC software. The driving control schematic is shown in Figure 3-8.

There are two modes: automatic and manual modes. In the automatic mode the green indicator light is “ON” in front of the driving box. The current automatically follows the setting current even if other parameters are changed. In the manual mode the blue indicator light is “ON”, and opening threshold can be set from 0 to 100%. A red alert is also set to notice the electrical warnings and wrong operations.

To get the constant current, an operational amplifier in current-source mode is used. The voltage changes with the load to compensate for the constant current flowing. Precise resistances are used to get accurate current. Maximum current of 2A and 2.5A can be selected. The constant current circuit is shown in Figure 3-9.

Detecting circuit is designed to test the forward current and voltage of LED, which is shown in Figure 3-10. The analog voltage and current signals are collected and transmitted by voltage follower and operational amplifiers, which convert them into digital signals. Then the data is fed back to MCU. Sampling resistances collect voltage signals and MCU converts them to actual LED currents.

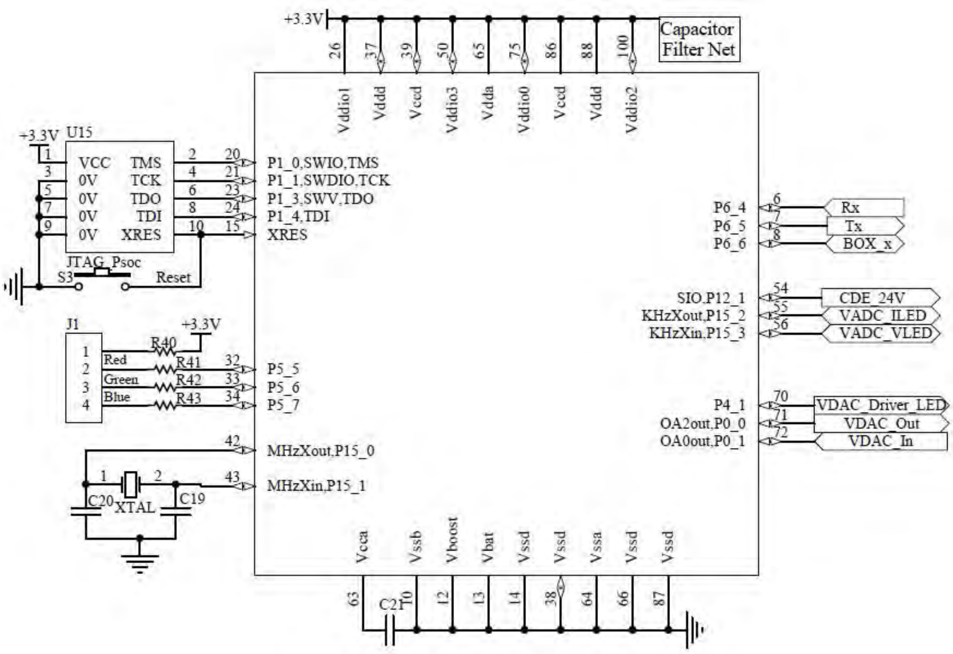


Figure 3-8 Driving control schematic

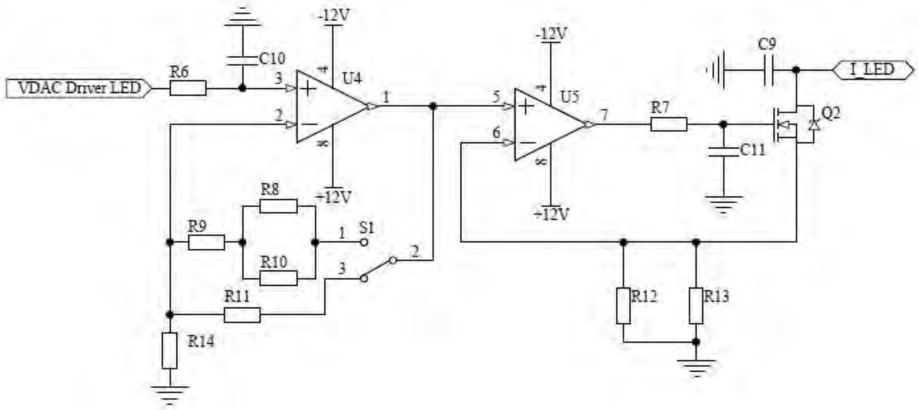


Figure 3-9 Constant current circuit

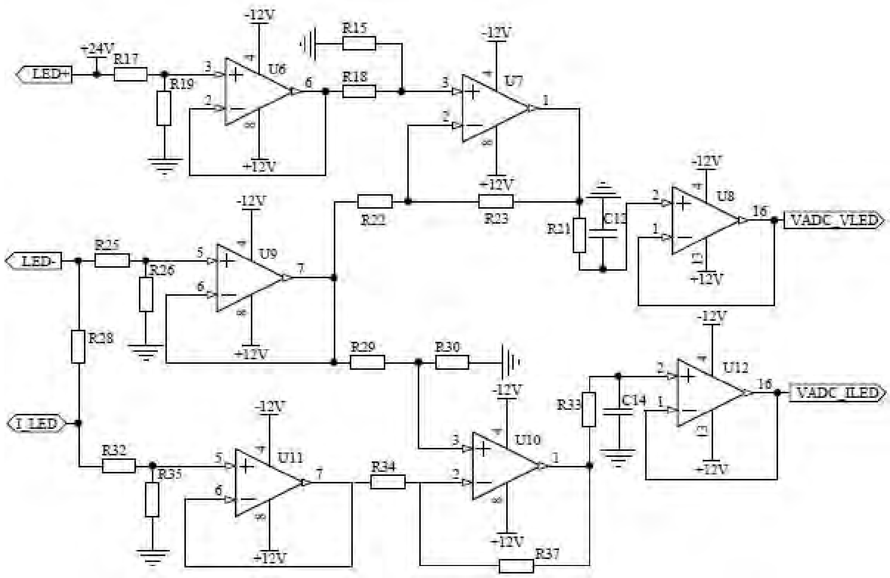


Figure 3-10 Detecting circuit for forward current and voltage of LED

3.2.5 PC software

In order to set and detect the real time parameters of LED, PC software is designed. It is available as a friendly operation interface communicating with the control box by USB. The parameters can be displayed in the software interface including the current set, frequency, duty cycle, output threshold and period. It can be set for individual channel and certain multi-channels. Besides, a command diagram in Excel can be imported to the software and displayed. After launching the commands, the system runs automatically according to the parameters and time sequences. The real-time curve for each parameter is displayed in the software and the data can be saved easily. The software interface is shown in Figure 3-11.

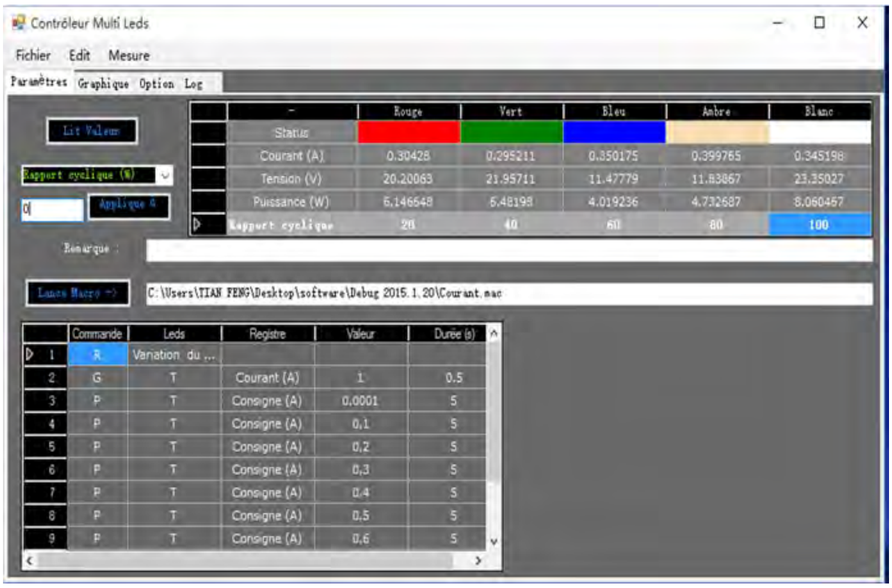


Figure 3-11 Software interface

3.3 Results and discussions

There are some technical performance parameters: output current 0-1A (2.5Amax), output voltage 0-24V, output power 0-24W, duty cycle 20-100% within 0.5A, frequency 0-100kHz, and actuator opening 0-100%. The real pictures of LED lighting system and main parts are shown in Figure 3-12.

LED lighting system

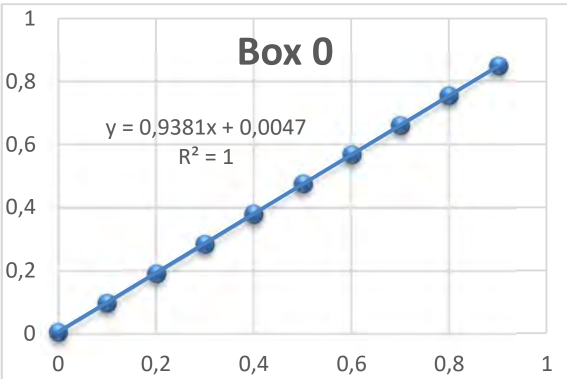
Electrical power

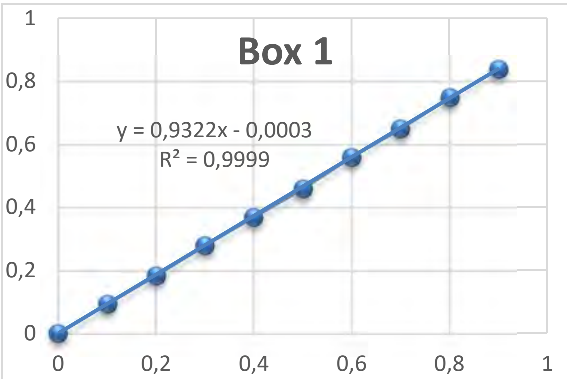
Control circuit

Driving circuit

Figure 3-12 The real pictures of LED lighting system and main parts

We tested four green LEDs in series. The current was set by PC software from 0 to 0.9A with 0.1A interval (abscissa axis), and the real current was measured by oscilloscope (vertical axis) (Figure 3-13). Meanwhile we compared the voltage in the software (abscissa axis) and the real voltage of LED (vertical axis) (Figure 3-14). The results show a linear relationship ($R^2 > 0.99$) between the set currents and the real currents, as well as the feedback voltages in the software and the real voltages. After calibration, for example box 1 (Figure 3-15), the setting currents well meet the real currents through the LEDs. Besides, Figure 3-16 shows the output ratios at 0.1A under different duty cycles and frequencies. The results indicate a power function relation between the output ratio and duty cycle, and a good consistency under different frequencies for 0.1A output current.





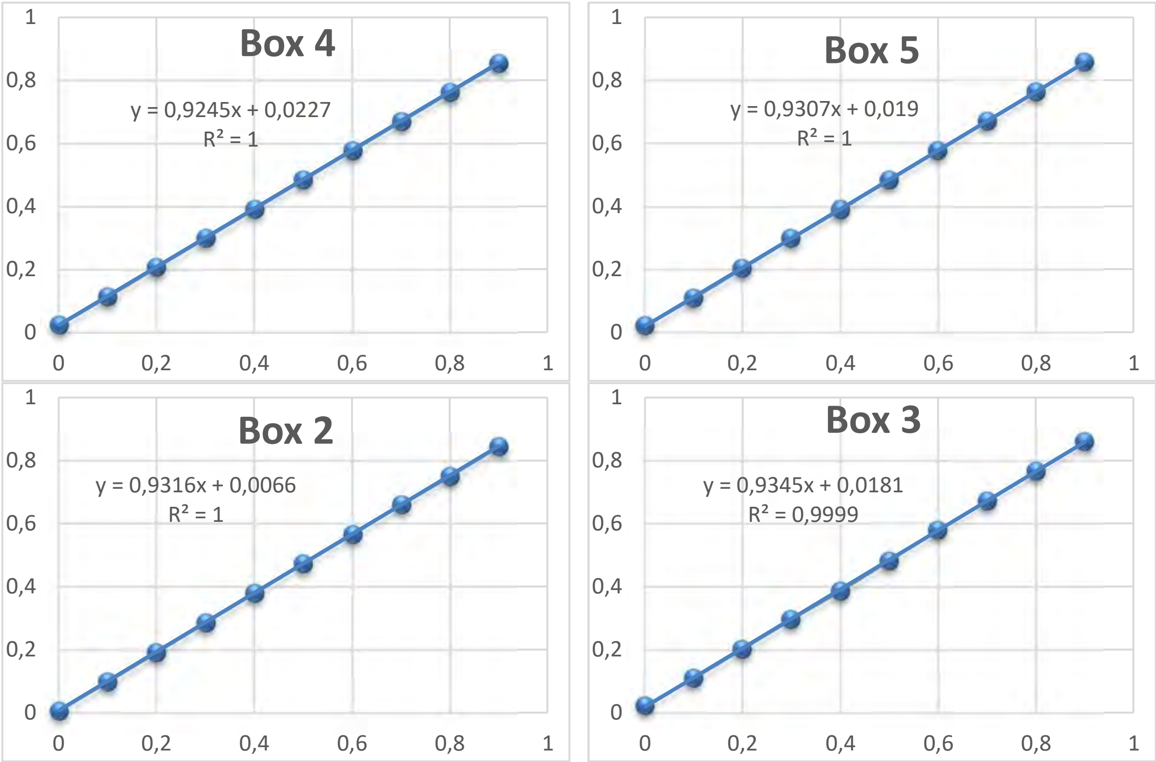
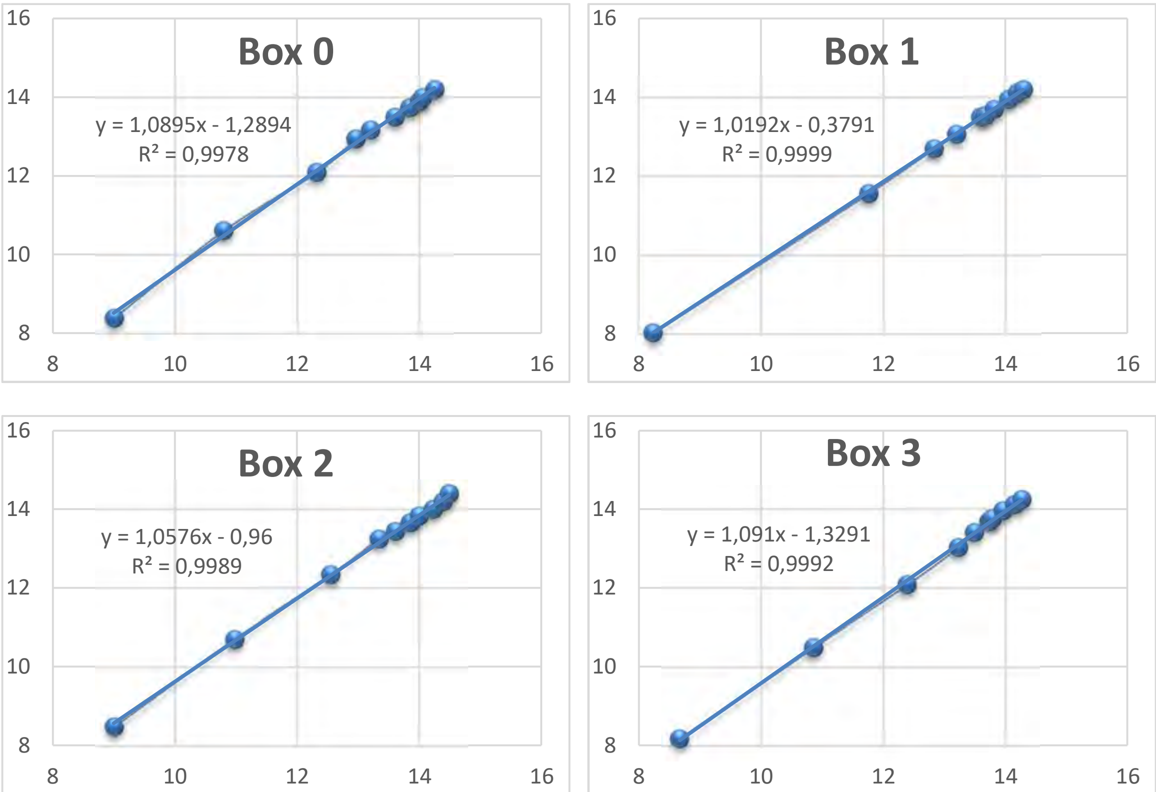


Figure 3-13 PC software current from 0 to 0.9A with 0.1A interval (abscissa axis) and the real current (vertical axis)



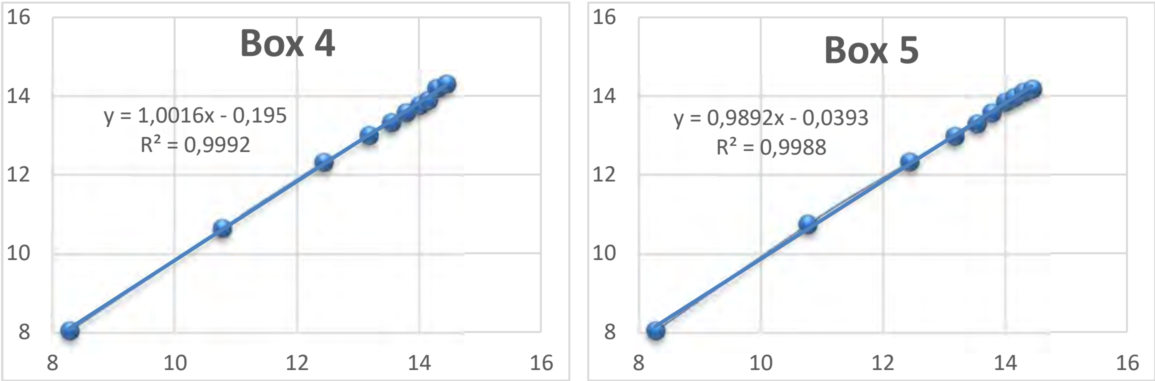


Figure 3-14 The voltage in the PC software (abscissa axis) and the real voltage of LED (vertical axis)

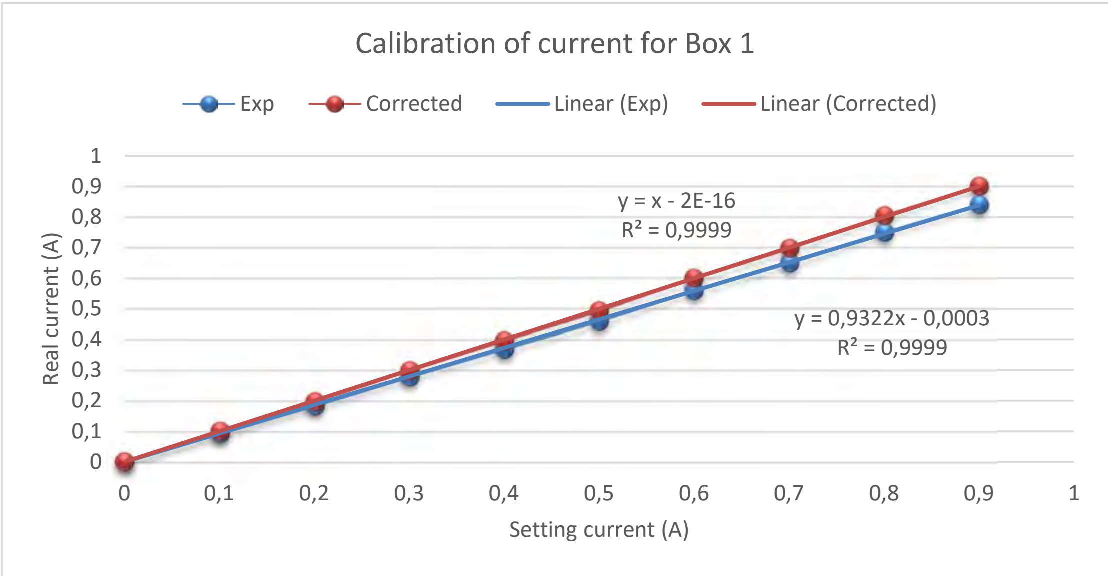


Figure 3-15 Calibration of current for Box 1

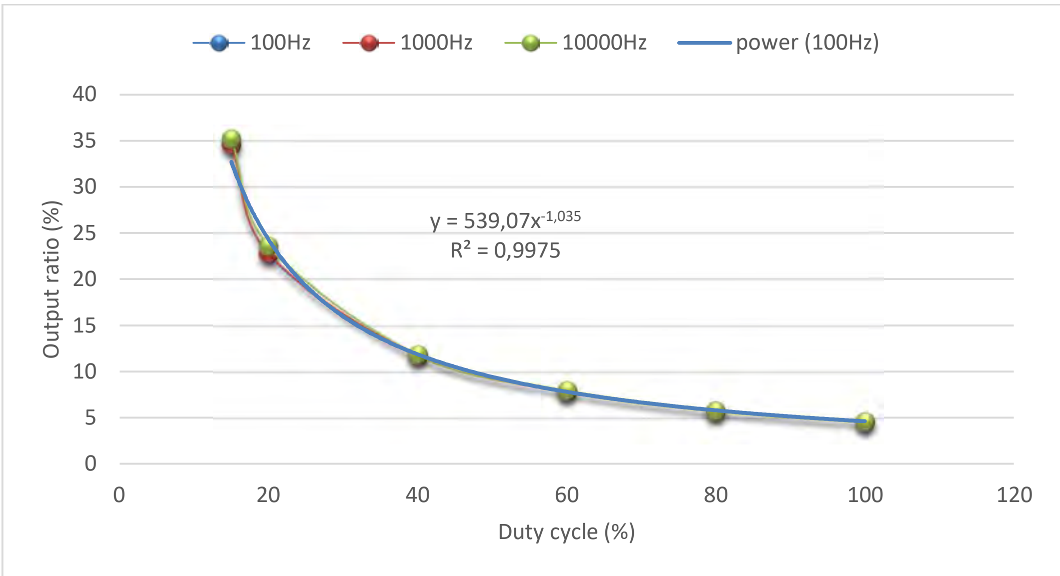


Figure 3-16 Output ratios at 0.1A under different duty cycles and frequencies.

3.4 Conclusion

In this chapter, a specific LED lighting system for greenhouse plant is designed featuring dynamic spectrum. Various working mode can be available arbitrarily by adjusting the current, frequency, duty cycle, period and the distribution of LEDs. The program based on the selective absorption spectrum of plant can be also controlled automatically. With these characteristics, the LED Lighting System can be used for the following experiments to provide both continuous and intermittent powers for LEDs.

Chapter 4
LED Lighting System Efficiency Measurement and Optimization

Synopsis

In this chapter, preliminary experimental results using the designed power supply are presented. LED Spectrum is tuned to match as best as possible the average plants based on relative quantum efficiency (RQE). Different spectra combinations were used to (re)create the full spectrum based on RQE curve for average plants. Different light measurement systems for plants were described including PPF, EPPF and YPF. A new concept of light measurement for plants was also described by phytometric system within the photosynthetically active radiation (PAR) of 400 to 700 nm. Besides, the light efficacy for plants was demonstrated by the application of five kinds of light emitting diode (LED).

In a second step, according to the principle of additive color mixture, both Gaussian function and real LED spectra were simulated in order to theoretically find the best combination of LEDs matching the RQE curve.

4.1 Introduction

LED light was first applied for plant in Japan in the early 1980s. Since the 90s, the semiconductor industry has a huge increase in the lighting field and achieved a series of major breakthroughs like blue LED which drive to white LED light. In the 21st century, many countries, including the USA, Netherlands, China, South Korea, Japan and Lithuania, have conducted various studies on the application of LED light to crop cultivation [31].

4.1.1 Relative quantum efficiency

Relative quantum efficiency (RQE) curve was made by McCree (1972a) based on the relative photosynthetic response to light of the average photosynthesizing plants, including grain crops: corn, sorghum, wheat, oats, barley, triticale and rice; oilseed crops: sunflower, soybean, castor bean and peanut; vegetable crops: lettuce, tomato, radish, cabbage, cucumber, cantaloupe and squash; miscellaneous: clover, cotton, sugar beet and pigweed, totally 22 species [87]. McCree carried on the experiment using the method of carbon fixation rates. The RQE curve, shown in Figure 4-1, indicates that plant photosynthesis is driven primarily in visible light. Spectra at 610nm and 440nm drive more photosynthesis. Other spectra such as green, yellow and amber have less impact on photosynthesis. Far-red and ultraviolet (UV) drive the minimum photosynthesis. The multiplication of the RQE curve with the spectral power distribution (SPD) of a given light source produced phytometric measurement with the units of $\mathrm{phytoW} \cdot m^{-2}$.

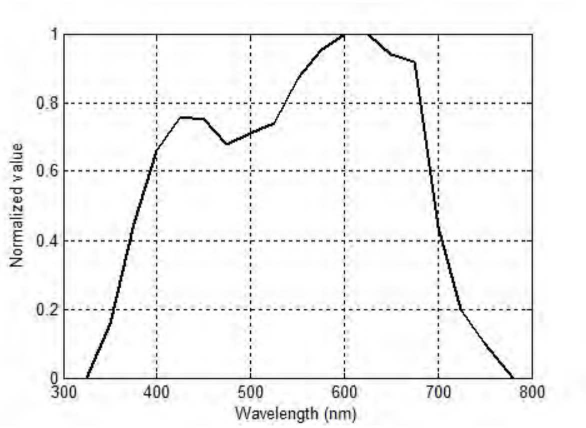


Figure 4-1 Relative quantum efficiency (RQE) curve

According to previous studies, red and blue light are the most efficient light for plant growth, but sometimes only using red and blue cannot provide optimal light quality, and may lead to mal-development, such as a nutrient deficiency, small size, disease, stagnation, even accelerated wither and die in the growth. For example, the main nutrients of human body include carbohydrates, lipids, proteins and water; the trace nutrients include vitamins, minerals and dietary fiber. Without the trace nutrients, human body would have some health problems. Similarly, plants could exhibit the same mechanism in the process of photosynthesis: red and blue spectra are the main light, the other wavelength within 400 to 700nm are the trace light. Considering that, full spectrum based on RQE is a great guarantee to produce healthy plants.

4.1.2 Photosynthetically active radiation

Plant photosynthesis is driven primarily by photosynthetically active radiation (PAR) from 400nm to 700nm that is absorbed by pigment molecules (mainly chlorophyll a and b and carotenoids, Figure 4-2) [88]. In the shorter wavelengths, photon's energy could be too strong and could damage cells and tissues, but they are mostly filtered out by the ozone layer in the stratosphere. In the longer wavelengths, photons do not carry enough energy for allowing photosynthesis to occur. Compared with other lighting types, supplementary use of UV light cannot be accurately regulated in greenhouses because of a lack of suitable and controllable UV light sources [31].

Until now many publications reveal the visible light effects to different plant growth, especially red and blue lights [89-91]. Photosynthetically active radiation (PAR) between 400-700nm is regarded as the main measurement.

Indeed, photosynthesis is fundamentally driven by photon flux rather than energy flux, but not all absorbed photons yield equal amounts of photosynthesis [88]. Whether we are considering the plant pigments or RQE curve, the spectral wavelengths between 400nm and 700nm (PAR) play a dominant role for plant growth.

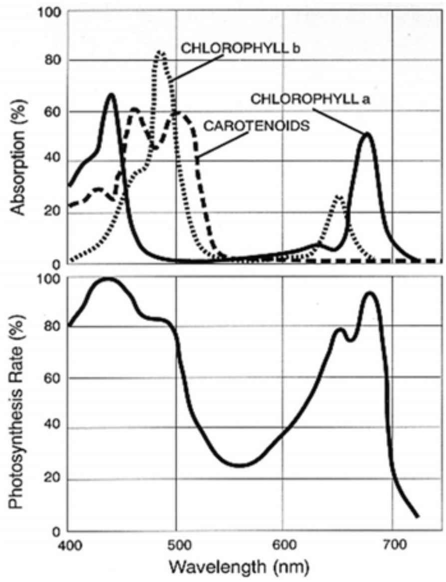


Figure 4-2 The absorption spectrum of chloroplast chlorophyll a and b and carotenoids along with the action spectrum of photosynthesis of a chloroplast

4.1.3 Light regime for plant growth

Plant Artificial Radiation Sources (PARS) have a long history for plant growth. This was mainly due to insufficient sun light caused by seasonal changes, geographic locations and bad weathers. For several decades, high pressure sodium (HPS) and tubular fluorescent lamps play a dominant role as the supplemental lighting. But now more efficient requirements are being proposed for greenhouse lighting, such as the light quality, quantity and photoperiod.

In order to optimize the spectrum for plant growth or algae, light regime should be considered. Light quality, quantity and photoperiod are three key parameters. The goodness of the three factors should be important criteria for superior lighting systems.

Light quality (320-780nm) refers to the spectral distribution of light. Suitable spectral combination of LED promotes plant growth. Different ratios of red and blue light are adopted in the papers. Some other colors such as white, green, yellow, far red and UV are also available. Blue (400-510nm) and red (610-720nm) spectra have the greatest impact for plants. From Figure 4-2 we can see the main pigments correspond to two peaks of photosynthetic rates [88]. It could be explained as the best absorption of red and blue spectra. But in reality, not all the absorbed photons take part in the photosynthesis. A series of complicated physical changes could occur when the light spectrum transmits the plant leaves. Except the reflected and transmitted light, the spectrum cannot be completely absorbed and used by the pigments, because of inactive pigments and transfer efficiency. Therefore, the absorption of pigment cannot be used as the sole criterion to determine the selective spectra of plant.

Light quantity (0-3000$\mu\text{mol} \cdot m^{-2} \cdot s^{-1}$) is the number of photons capable of performing photosynthesis. Light intensity and daily light integral are two main measuring methods. The light quantity can affect the growth rate of the plant. Too high intensity could damage plant tissues and organs.

Photoperiod is the developmental responses of plants to the relative lighting's time lengths and dark periods. Photoperiodic responses in plants are regulated by special pigments known as phytochromes. Some plants may need only few hours of light a day while others (full sun plants) need eight hours or more. Some plants and algae have the self-regulation function to acclimatize dynamic light environment, such as different frequencies of pulse light.

4.2 Experimental results

4.2.1 RQE curve fitting using additive color mixing with five colored channels.

We tried to form RQE curve with five LED colors by five channels. The five LED colors are shown in Figure 3-2. The spectrum was measured in the integrating sphere by adjusting the forward current of each LED. According to the principle of additive color mixture, the spectrum formed by red, amber, green, blue and cool white is shown in Figure 4-3. In this case, the result is unsatisfactory. After analysis, the coefficient of determination (R^2) is very low, only 0.4613.

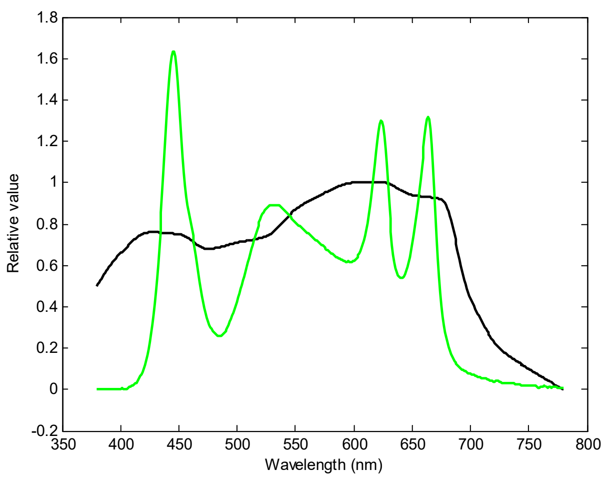


Figure 4-3 Spectrum formed by five LED colors: red, amber, green, blue and cool white

It was suspected that the cool white was not adapted, because the errors in the blue region were quite high. A warm white LED was therefore used to attempt to reduce the errors. The spectrum formed by red, amber, green, blue and warm white is shown in Figure 4-4. In this case, the result is much better than cool white. The R^2 is about 0.5924. Even if improved performances are obtained, results are still not good enough to achieve optimal spectrum characteristics.

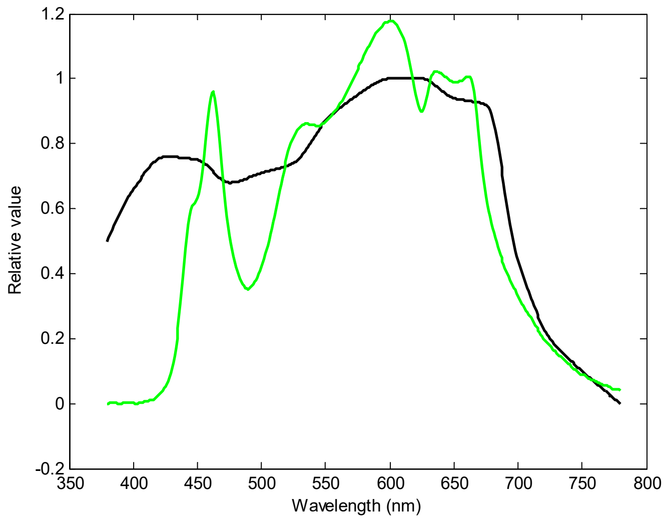


Figure 4-4 Spectrum formed by red, amber, green, blue and warm white

With only five channels, the LED lighting system is not able to deliver a spectrum that match accurately the RQE curve. As it will be shown in session 4.3.3, more LEDs should be used in order to accurately fit RQE curve.

4.2.2 Spectrum efficiency for plants

As we know, the photometric system is based on the response of the average human eye to light. The spectral luminous efficiency values for photopic vision was established in 1931 by the Comission Internationale de l'Eclairage [92]. However, the spectral sensitivities of plants are quite different with human eye. How plants interact with light provides the basis for three principal physiological processes: photosynthesis, photomorphogenesis and photoperiodism, which govern the plant growth and development.

There are three existing systems of light measurement: the radiometric, the photometric and the quantum system. Each system has its own light sensor. The ideal response curve for the radiometric sensor is a flat horizontal line parallel to the x-axis. For the photometric system, the ideal response curve is a bell curve following the human retina sensitivity. Meanwhile, the ideal response curve for the quantum system can be a positively-sloped line (photon-flux) or a flat horizontal line parallel to the x-axis (equal photon-flux) (Figure 4-5) [93]. According to extensive literature reviews [94-97], McCree defined relative quantum efficiency (RQE) curve and provided a comprehensive set of data based on 22 average photosynthesizing plant species. After, the RQE curve was successfully replicated by Inada [98], and refined by Sager [99]. The RQE curve reveals that the photosynthetic response of plants to light is not uniform across wavelengths, but with peaks in the red and blue spectra, and lower response in the green region. Therefore, for plant applications we should use the plant basis. In this part the photosynthetic response was calculated using different light measurement systems dedicated to plants: EPPF, PPF, YPF and the new measuring system of phytometric.

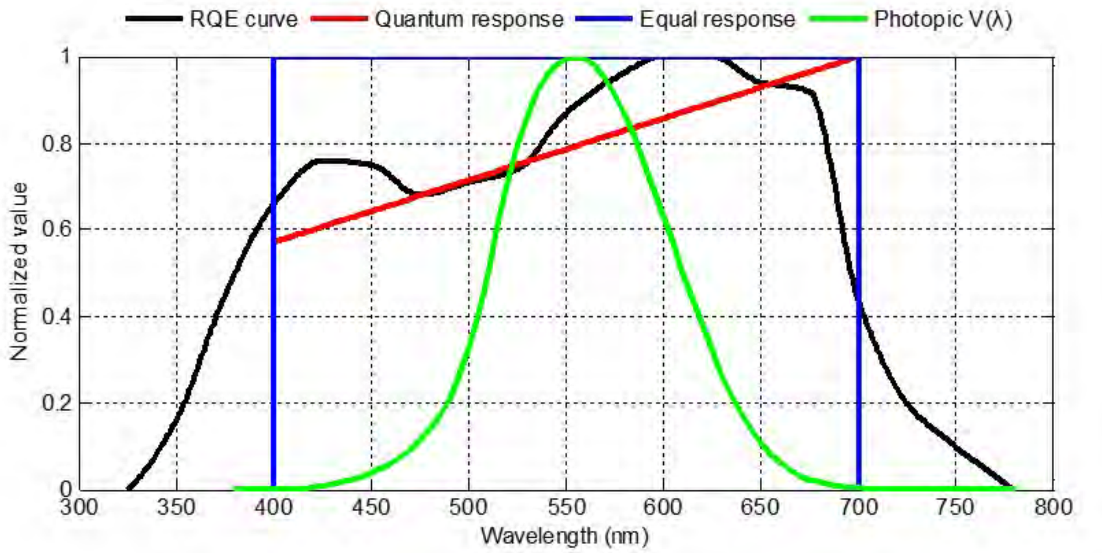


Figure 4-5 The normalized spectral sensitivity of human eye (photopic $V(\lambda)$), the ideal response curve for the quantum system (PPF and EPPF) and RQE curve

4.2.2.1 Light measurement systems for plants

For the photometric system of human eye, the light quantities are calculated by a multiplication of the spectral power distribution (SPD) with the spectral luminous efficiency function V(λ) of the standard observer. For average photosynthesizing plants, photosynthetic photon flux (PPF), yield photon flux (YPF), equal photosynthetic photon flux (EPPF), and phytometric system are usually adopted.

Mathematically, the spectral quantity distribution (Q) of a light source can be represented by the general equation (7). [93]. Q can be a flux, an intensity, an irradiance, an emittance or a normalized value, depending on its specific designation and unit [100-103]. Because the $R(\lambda)$ and $Q(\lambda)$ cannot be expressed by simple functions, the equation can use the discrete form (equation (8).), which is easier to solve.

$$Q = \int_{\lambda 1}^{\lambda n} R(\lambda) \cdot \mathrm{Q}(\lambda) \cdot d\lambda \quad (7).$$

$$Q = \sum_{\lambda 1}^{\lambda n} R(\lambda) \cdot \mathrm{Q}(\lambda) \cdot \Delta\lambda \quad (8).$$

Where, $R(\lambda)$ is the response of the ideal or real sensor as a function of the wavelength,

and $Q(\lambda)$ is the spectral radiant energy of the source per unit wavelength (λ) interval.

4.2.2.1.a PPF

Photosynthesis is driven by the number of photons that a plant receives and not by the energy of the photons. Photosynthetically Active Radiation (PAR) describes the moles of photons in the radiant energy spectral range between 400-700nm which are used by plants for photosynthesis. There are two main ways to measure PAR: PPF (PPFD) and YPF. PPF is a measure of all the photons a light source emits per second within the PAR range (400-700nm). Photosynthetic Photon Flux Density (PPFD) is the number of photons per second per unit area within the PAR range. PPFD is an important measurement when determining if a horticulture light is sufficient for a specific plant.

In the radiometric photo flux system, $R(\lambda)$ is defined as the reciprocal of energy per mole photons at the wavelength of λ (equation (9).) in unit of $\mu\text{mol} \cdot m^{-2} \cdot s^{-1} \cdot nm^{-1}$ [104]. Less light energy is needed for the same number of photons by using longer wavelengths and therefore for the same amount of photosynthesis. Thus, the equation for PPF can be expressed by equation (10).. The light efficacy (η_{PPF}) for plants based on PPF is defined as the ratio of PPF to radiant flux of the light source (equation (11).).

$$R(\lambda) = \frac{\lambda}{Nhc} = \frac{\lambda}{119{,}6266} \tag{9.}$$

$$PPF = \int_{\lambda 1}^{\lambda n} R(\lambda) \cdot \mathrm{S}(\lambda) \cdot d\lambda \tag{10.}$$

$$\eta_{PPF} = \frac{\int_{\lambda 1}^{\lambda n} R(\lambda) \cdot S(\lambda) d\lambda}{\int_{\lambda 1}^{\lambda n} s(\lambda) d\lambda} \tag{11.}$$

R(λ): The reciprocal of energy per mole photons

S(λ): Relative spectral power distribution of a light source

η_{PPF}: The light efficacy for plants based on PPF

N: Avogadro constant: $6.02214129(27) \cdot 10^{23}\ mol^{-1}$

h: Plank constant: $6.62606957(29) \cdot 10^{-34}\ J \cdot s$

c: Speed of light: $299792458\ m \cdot s^{-1}$

4.2.2.1.b EPPF

When photons of light are weighted equally over a range of wavelength, Equal Photosynthetic Photon Flux (EPPF) can be calculated. In the spectral luminous efficiency function V(λ) for photopic vision, the peak wavelength at 555.016 nm has the highest luminous efficiency of 683.002 lm/W. Similarly, in the spectral efficiency function of plants RQE(λ), λ=610nm has the highest amount of photosynthesis per photon according to RQE. Thus,

$$R(\lambda) = \frac{\lambda}{Nhc} = \frac{610}{119{,}6266} = 5{,}1 \tag{12.}$$

$$EPPF = \int_{\lambda 1}^{\lambda n} R(\lambda) \cdot \mathrm{S}(\lambda) \cdot d\lambda \tag{13.}$$

$$\eta_{EPPF} = \frac{\int_{\lambda 1}^{\lambda n} R(\lambda) \cdot \mathrm{s}(\lambda) d\lambda}{\int_{\lambda 1}^{\lambda n} \mathrm{s}(\lambda) d\lambda} \tag{14.}$$

η_{EPPF}: The light efficacy for plants based on EPPF

4.2.2.1.c YPF

YPF is a more accurate measure of a horticulture lights ability to drive photosynthesis. This method of measurement emerged because PPFD does not take into effect that all photons (light quantum) drive photosynthetic rates differently. YPF shows how efficiently plants use each different wavelength of light in the PAR region.

$$YPF = \int_{\lambda 1}^{\lambda n} R(\lambda) \cdot RQE(\lambda) \cdot \mathrm{S}(\lambda) \cdot d\lambda \tag{15.}$$

$$\eta_{YPF} = \frac{\int_{\lambda 1}^{\lambda n} R(\lambda) \cdot RQE(\lambda) \cdot \mathrm{S}(\lambda) \cdot d\lambda}{\int_{\lambda 1}^{\lambda n} s(\lambda) \cdot d\lambda} \tag{16.}$$

η_{YPF}: The light efficacy for plants based on YPF

4.2.2.1.d Phytometric system

Phytometric system is based on the photosynthetic response of the average photosynthesizing plant. The relative quantum efficiency was adopted as the basis. Phytometric flux (Φ_{Phyto}) is the multiplication of the spectral power distribution with the normalized RQE curve ($RQE(\lambda$).

$$\Phi_{Phyto} = \int_{\lambda 1}^{\lambda n} RQE(\lambda) \cdot S(\lambda) \cdot d\lambda$$

$$\eta_{phyto} = \frac{\int_{\lambda 1}^{\lambda n} RQE(\lambda \cdot S(\lambda) d\lambda}{\int_{\lambda 1}^{\lambda n} s(\lambda) d\lambda} \qquad (17).$$

η_{phyto}: The light efficacy for plants based on phytometric

4.2.2.2 Results and discussions

Five LED colors: red, amber, green, blue and white are tested and deduced for PPF, EPPF, YPF and phytometric flux. The results with normalized spectral power distributions and tested ones at nominal currents are discussed within PAR region.

4.2.2.2.a Results of normalized spectrum

The normalized spectral power distributions for the five LEDs are shown in Figure 4-6, where the solid lines represent radiometric power distribution, and the dashed lines represent relative phytowatt distribution. The normalized results were calculated by the normalized LED spectra and the ideal response curve (or sensor) of PPF, EPPF, YPF and phytometric response. For the normalized spectrum, the results of each light measurement depend on the integrated radiant flux. The results for EPPF follow the order $\mathrm{white} > \mathrm{green} > \mathrm{blue} > \mathrm{red} > \mathrm{amber}$ (Table 4-1). So the spectral width for each spectrum can be deduced by the EPPF function, following the order $\mathrm{green} > \mathrm{blue} > \mathrm{red} > \mathrm{amber}$, which means the relative radiant flux following the same order. The results for PPF, YPF and phytometric follow the same order $\mathrm{white} > \mathrm{green} > \mathrm{red} > \mathrm{amber} > \mathrm{blue}$. White LED spectrum account for the maximum relative radiant flux, so it has the maximum values for all the measurements. Green LED spectrum has relative higher values for EPPF due to a larger spectral width, following the order $\mathrm{green} > \mathrm{blue} > \mathrm{red} > \mathrm{amber}$. However, PPF values of red and amber spectrum become bigger than blue. This is because that with the same energy, longer wavelengths have more photons than shorter wavelengths, and can drive more photosynthesis within PAR region. It shows the same cases and reasons for YPF and phytometric (Φ_{Phyto}).

For the light efficacies, η_{EPPF} have the same value because photons of light are weighted equally over the PAR range. For η_{PPF}, it follows the order $\mathrm{red} > \mathrm{amber} > \mathrm{white} > \mathrm{green} > \mathrm{blue}$. The light efficacies decrease with the decreasing wavelength. For η_{YPF} and η_{phyto}, amber spectrum performs the best because of the maximum efficiency region of RQE curve. White spectrum displayed a medium light efficacy for η_{PPF}, η_{YP} and η_{phyto}. This could be explained by a combination of different wavelengths of white light, which would presumably perform a mixed effect of whole light spectrum.

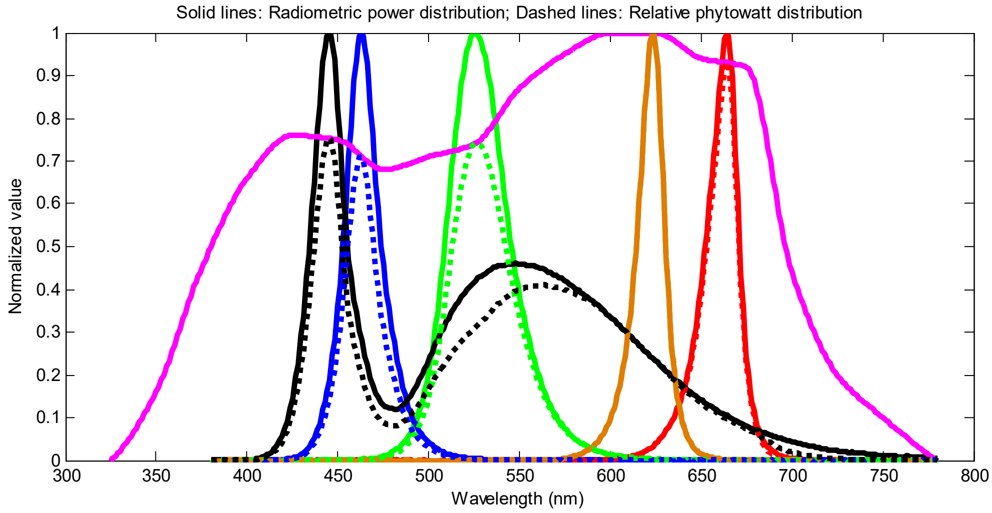


Figure 4-6 Normalized spectral power distribution for five LED colors

Table 4-1 Results for PPF, EPPF, YPF and phytometric measurements with normalized spectrum

	Red	Amber	Green	Blue	White
PPF	21.5446	17.9372	32.1131	17.2800	64.9868
EPPF	19.9428	17.6278	36.9407	22.6413	74.4095
YPF	22.4079	19.9403	28.0621	13.7386	61.4440
Φ_{Phyto}	21.3233	20.1367	33.0646	18.5082	71.3426
η_{PPF}	0.9414	0.8867	0.7575	0.6651	0.7611
η_{EPPF}	0.8714	0.8714	0.8714	0.8714	0.8714
η_{YPF}	0.9791	0.9857	0.6620	0.5288	0.7196
η_{phyto}	0.9318	0.9955	0.7800	0.7124	0.8355

4.2.2.2.b Results of real spectrum at nominal current

The tested spectral power distributions for the five LEDs at nominal currents are shown in Figure 4-7. What we should note is PPF that measured by a specific PAR sensor (specbos 1201). The red and blue spectra have the maximum values for PPF, EPPF and phytometric system (Table 4-2), which correspond the main absorption regions of chlorophyll a and b. For YPF, it is a more accurate light measurement for plants. The results show that YPF in the red region is 1.55 times as big as the YPF in the blue region. That is why more red light is adopted than blue light in many references. Red light supplemented with a certain amount of blue light has a great benefit for plant growth. For all the measurement, the green light shows the minimum quantities. That is because much of green spectrum is reflected or transmitted by the leaves, so it is not as important as red and blue light. For the light efficacies, they have the same trend with the results of normalized spectrum.

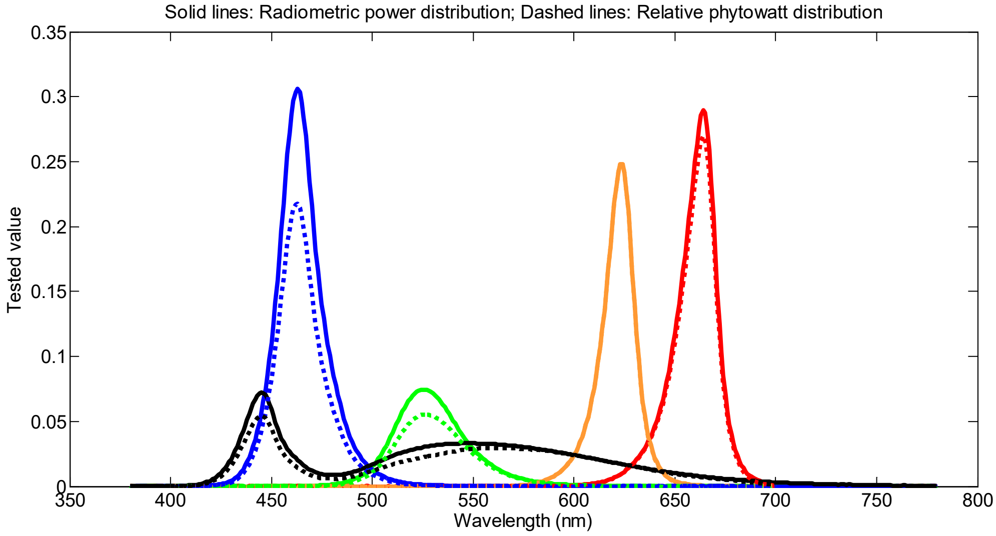


Figure 4-7 Tested spectral power distribution for five LED colors

Table 4-2 The tested results of PPF and deduced results of EPPF, YPF and phytometric measurements

	Red	Amber	Green	Blue	White
PPF	36.5189	26.0407	14.0175	30.9335	27.4009
EPPF	33.8091	25.5955	16.1273	40.5373	31.3788
YPF	34.0113	25.9222	10.9686	22.0226	23.1986
Φ_{Phyto}	6.1768	4.9959	2.4665	5.6621	5.1407
η_{PPF}	0.8768	0.8258	0.7055	0.6194	0.7088
η_{EPPF}	0.8117	0.8117	0.8117	0.8117	0.8117
η_{YPF}	0.8165	0.8221	0.552	0.441	0.6001
η_{phyto}	0.9318	0.9955	0.7800	0.7124	0.8355

4.3 Simulation of LED spectrum for average plants

As it was mentioned before, additive mixing of 5 colored channels cannot successfully reproduce the RQE curve. In this paragraph, Gaussian function model was used to simulate single LED spectrum at a given central wavelength. Then we use multiple LED models to simulate the RQE curve between 320 nm and 780 nm, which represent the full spectrum or optimal spectrum for plant growth. Then, we chose 12 available LED spectra to fit the RQE curve. From the simulations, we can get the relative parameters and the ratio of each LED spectrum. For different plants, we can easily modify the coefficient of LED spectra to realize the best illumination.

4.3.1 Smoothness of RQE curve

RQE curve was the relative photosynthetic response to light based on 22 average photosynthesizing plants. Normally, the photosynthetic response to light of plants should smoothly change with the wavelength. Thus, RQE curve was improved based on several points in the document tested by McCree. With Matlab software, four fitting methods were adopted: nearest, linear, spline and cubic (Figure 4-8). Cubic fitting presents the best result, so it will be a basis for the following calculations.

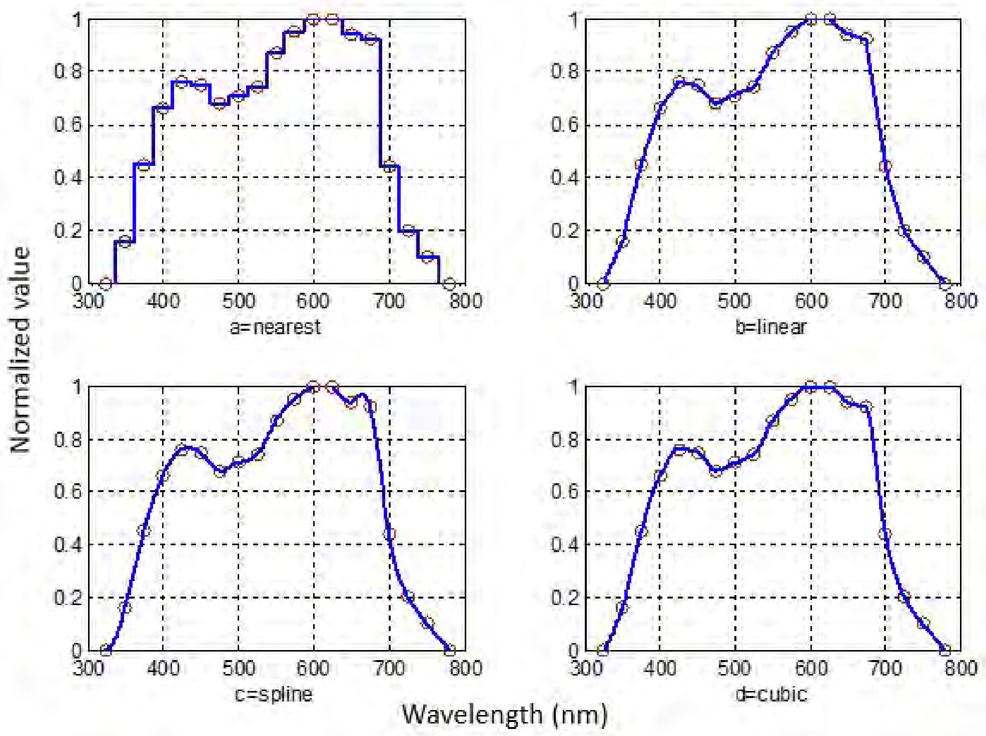


Figure 4-8 Improved RQE curve with four fitting methods: nearest, linear, spline and cubic

4.3.2 Simulation with multi-term Gaussian model

In this part, multi-term Gaussian model was used to simulate the optimal spectrum for average plants with Matlab optimization toolbox. The function is shown in equation (18).. Simulations with 2, 4, 6, 8 term Gaussian model are shown in Figure 4-9. Goodness of fitting by 3 to 8 term Gaussian model is shown in Figure 4-10.

$$S(\lambda_{pi}, \lambda_{FWHMi}, \lambda) = A_1 \cdot \exp\left(-\left(\frac{\lambda-\lambda_{p1}}{\lambda_{FWHM1}}\right)^2\right) + A_2 \cdot \exp\left(-\left(\frac{\lambda-\lambda_{p2}}{\lambda_{FWHM2}}\right)^2\right) + \cdots + A_i \cdot \exp\left(-\left(\frac{\lambda-\lambda_{pi}}{\lambda_{FWHMi}}\right)^2\right) + \cdots$$

$$i = 1, 2, 3, \cdots \qquad (18).$$

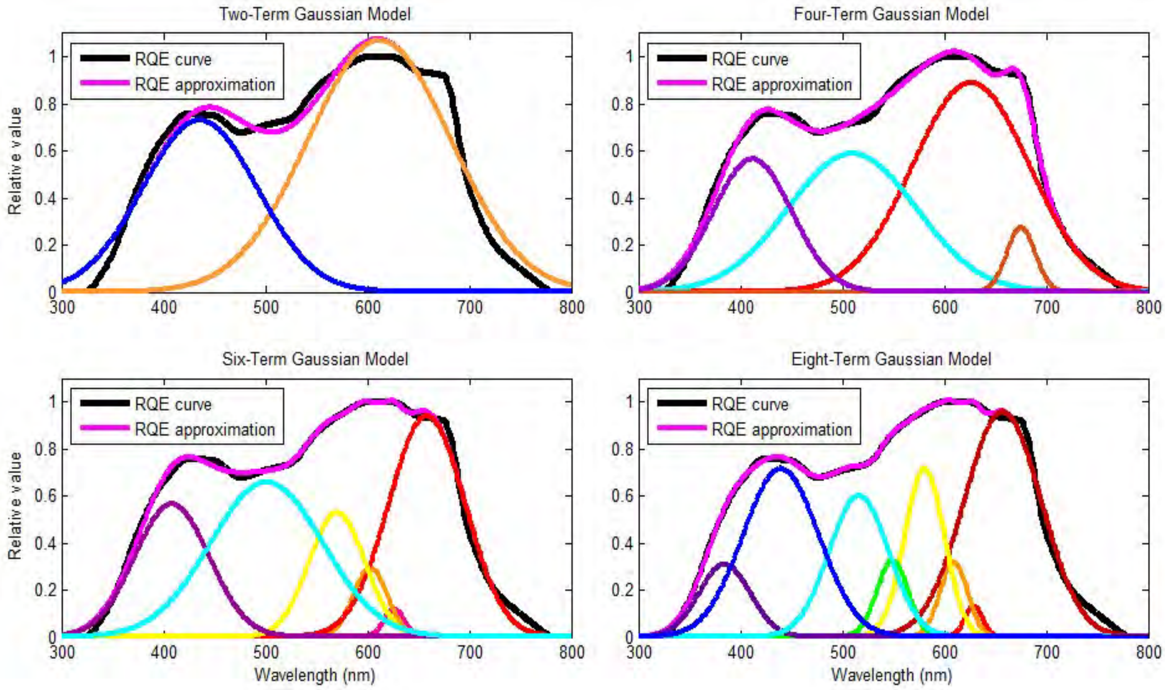


Figure 4-9 RQE simulations with 2, 4, 6, 8 term Gaussian model

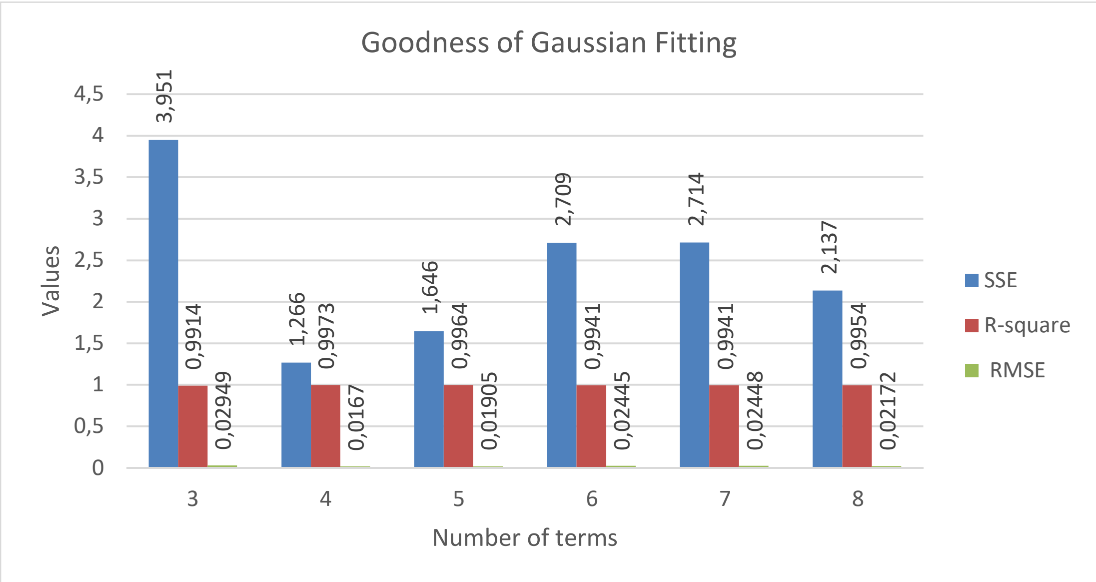


Figure 4-10 Goodness of Fitting simulated by 3 to 8 term Gaussian model

When the term of Gaussian model is more than 3, the values of determination (R^2) is more than 0.99, and root mean square error (RMSE) is less than 0.03. However, the λ_{FWHMi} is too large to find matched LED. Even with eight-term Gaussian model, it has a λ_{FWHMi} more than 50nm (Table 4-3). So large spectral width is very difficult or not available to get from the manufactures.

Normally, LED without phosphor has good monochromaticity; for red and blue LED, $\lambda_{FWHMi} \approx 25nm$; for amber LED, $\lambda_{FWHMi} \approx 20nm$; for green LED, $\lambda_{FWHMi} \approx 30nm$; so it is necessary to set the boundary of parameters in the Gaussian models.

In order to make the simulation of practical significance, λ_{FWHMi} is limited less than 25nm; A_i is limited between 0 and 1; and λ_{pi} is limited between 300nm to 800nm. So it would be easier to get such kind of LED from the manufacturers. Twelve-term Gaussian model was used to get the optimized spectrum. The result is shown in Figure 4-11 (R^2 = 0.98).

Table 4-3 The values of λ_{FWHMi} 2, 4, 6, 8 term Gaussian model

	λ_{FWHM1} (nm)	λ_{FWHM2} (nm)	λ_{FWHM3} (nm)	λ_{FWHM4} (nm)	λ_{FWHM5} (nm)	λ_{FWHM6} (nm)	λ_{FWHM7} (nm)	λ_{FWHM8} (nm)
2-term Gaussian	99.24	79.65						
4-term Gaussian	81.09	88.98	19.89	54.79				
6-term Gaussian	14.07	23.69	52.81	38.9	51.84	78.27		
8-term Gaussian	12.59	19.14	**53.43**	27.46	21.73	35.74	41.47	**52.78**

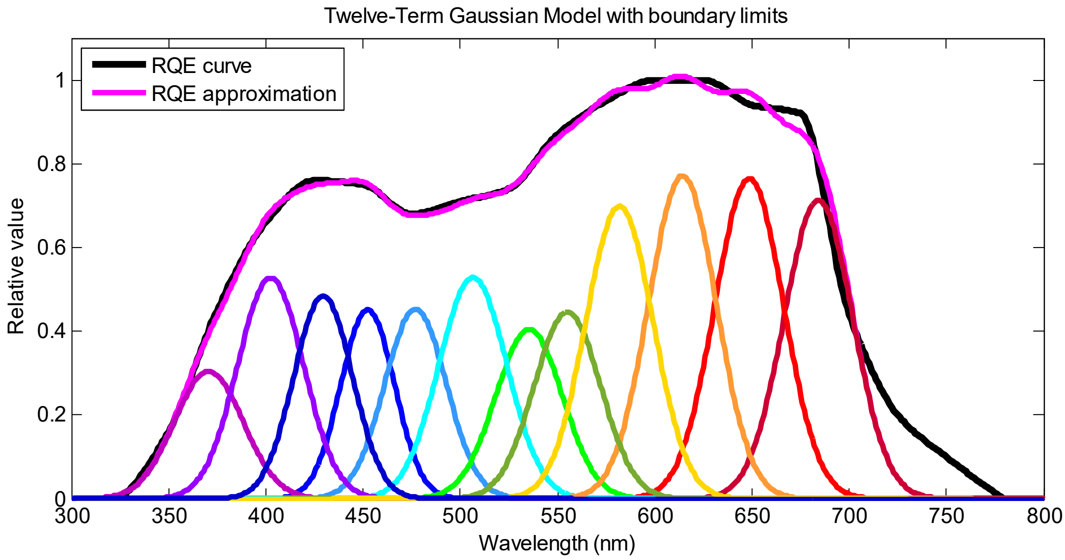


Figure 4-11 Twelve-term Gaussian model with boundary limits for RQE simulation

All the parameters for twelve-term Gaussian model are shown in Table 4-4. In this case, all the spectral widths are less than or equal 25 nm. The rate represents the ratio of spectral quantity of single LED to the whole spectral quantity (sum of 12 LEDs). On the premise of well controlling the junction temperature (T_j) of LED, we can assume that the spectral quantity has a linear relationship with the forward current (I_f); if the relationship between I_f and A_i is found, the real spectrum could be realized.

Table 4-4 Values of fitting parameters for 12-term Gaussian model

i	A_i	λ_{pi} (nm)	λ_{FWHMi} (nm)	Rate (%)
1	0.3043	370.7	24.98	4.87
2	0.5274	402.5	23.92	8.08

3	0.4847	429.5	21.3	6.61
4	0.4515	452.4	19.48	5.63
5	0.4527	477	22.47	6.51
6	0.5285	506.5	24.68	8.35
7	0.4039	535.4	24.37	6.30
8	0.4461	555.1	24.15	6.90
9	0.6989	581.9	24.44	10.94
10	0.7709	614.3	24.61	12.15
11	0.7651	648.6	25	12.25
12	0.7129	684.2	25	11.41

Note: "Rate (%)" represents the ratio of spectral quantity of single LED to the whole spectral quantity (sum of 12 LEDs)

4.3.3 RQE simulation with 12 LED spectra within PAR

Twelve real LED spectra were used for simulation within PAR (400 nm to 700 nm). The peak wavelengths used are 405 nm, 420 nm, 430 nm, 445 nm, 460 nm, 475 nm, 490 nm, 505 nm, 545 nm, 660 nm, 680 nm and warm white (2700K). The spectra of LEDs are shown in Figure 4-12. The white warm LED has the maximum ratio of 55.13% and then 430 nm with a ratio of 8.24%, and 545 nm with a ratio of 12.90% (Table 4-5). In this case, the warm white LED plays a dominant role to simulate the RQE curve, which account for more than a half, especially in the red region. For the other LEDs, more than half kinds of LEDs gather near the blue region, and each LED accounts for a small rate. Thus, taking the warm white as a core spectrum and the others as supplemental spectra, the full RQE spectrum was created for average photosynthesizing plants.

What the LED lighting system does is to provide dynamic and flexible powers for LEDs. So the optimal spectrum could be available by adjusting the light quality, quantity and photoperiod. The LED types determine the light quality, and the system determines the light quantity and photoperiod. Though the simulation, twelve LEDs are able to create a nice full spectrum for average plants. Thus, another seven channels are required. This work will be easy to do. The further study is more important for application and optimization of LED spectrum for *S. platensis* growth in Chapter 5.

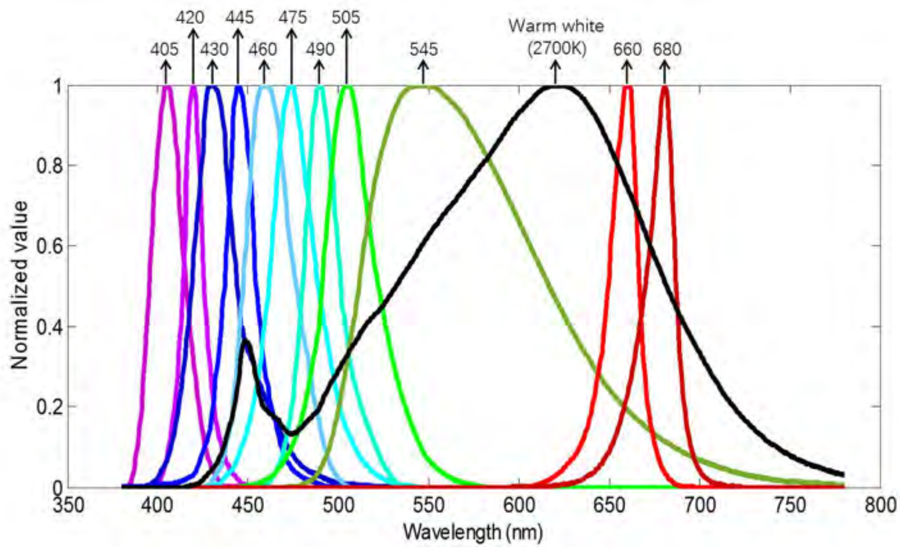


Figure 4-12 Twelve LED spectra adopted

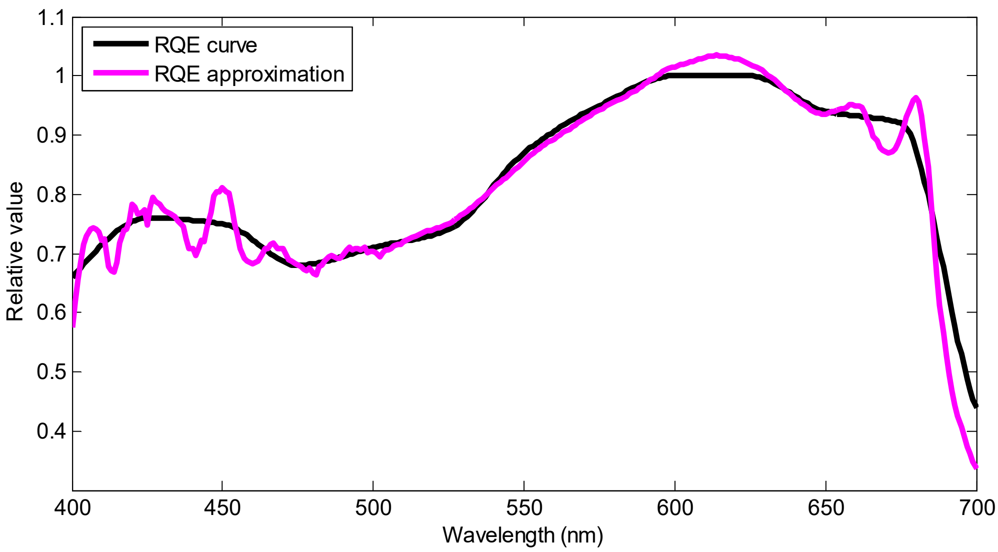


Figure 4-13 RQE simulation with 12 LED spectra within PAR

Table 4-5 Values of fitting parameters for 12 LED spectra

i	A_i	λ_{pi} (nm)	Rate (%)
1	0.67	405	4.52
2	0.19	420	1.14
3	0.63	430	8.24
4	0.10	445	0.90
5	0.20	460	2.59
6	0.33	475	4.32
7	0.22	490	2.27

8	0.19	505	2.86
9	0.2871	545	12.90
10	0.13	660	1.13
11	0.46	680	4.00
12	0.89	White (2700K)	55.13

Note: "Rate (%)" represents the ratio of spectral quantity of single LED to the whole spectral quantity (sum of 12 LEDs)

4.4 Conclusion

It is shown that the 5-channel LED lighting system is not able to match perfectly the RQE curve. Nevertheless, this system combined with theoretical investigations enables us to quantitatively evaluate wavelength efficiency on average plant growth. It is moreover demonstrated that results differ significantly according the measurement systems used (PPF, EPPF, YPF or phytometric).

The test results from specbos 1201 show that red and blue spectra have the maximum PPF, which correspond the main absorption region of chlorophyll a and b. YPF, a more accurate light measurement for plants, shows a much bigger value in the red region, which is 1.55 times as big as the YPF in the blue region. For all the measurement, the green light has a minimum quantity.

Finally, a theoretical study is presented. LED spectrum is approximated with Gaussian function. Results can be used to define LEDs characteristics, such as the peak wavelength, half spectral width as well as the ratio of each spectrum, to match the RQE curve as much as possible. Through the simulation of 12 LED spectra, we found warm white LED could play a dominant role for RQE curve, the others could be used as supplemental spectrum.

Chapter 5
Application to *Spirulina Platensis* Culture

Synopsis

Spirulina platensis (*S. platensis*) is known as the best health care product in the 21st century. However, the specific growth rate should be further improved by the efficient high-power LEDs. In this chapter, PPF was used as the light measurement for *S. platensis* because YPF and phytometric were specific for average plants (see Chapter 4). The light requirement for *S. platensis* was analyzed according to the major pigments and PI (photosynthesis irradiance) curve. The absorbance of *S. platensis* was measured by a special design of test container based on beer's law. In order to get the optimal spectrum, we used various kinds of LEDs with different spectra, intensities, powers, light distributions and patterns to cultivate *S. platensis*. The Monod model was improved to properly evaluate the specific growth rate (µ). The mathematical model of PI curve was developed for the photosynthesis rate (P^B) of *S. platensis*, which was favorable to understand light-limited, light-saturated, photo-inhibited and photo-acclimated regions. Besides, the economic efficiency was also discussed for the best harvest time and optical density (OD) of *S. platensis*.

The normalized or relative values will be used for experimental results to protect the intellectual property. This project was also supported by the program EPICURE funded by Region Midi-Pyrénées and European FEDER.

5.1 Spirulina platensis

Microalgae have been studied in the laboratory and in mass outdoor cultures for more than a century. Since 1940s, microalgae have been grown for a variety of potential applications, such as the success of wastewater treatment, the production of lipids for energy, anti-microbial substances, bio-chemicals and cheap proteins for human nutrition. In recent years, bioenergy produced by microalgae have been researched as a popular topic [105].

S. platensis is a filamentous cyanobacterium (diameter of 10 µm and length of tens to hundreds of µm), and planktonic blue-green algae (Figure 5-1), which can be consumed by humans and other animals as a dietary supplement or a whole food. There are two species: *Spirulina (Arthrospira) platensis* and *Spirulina maxima*. They can grow in both fresh and salt water.

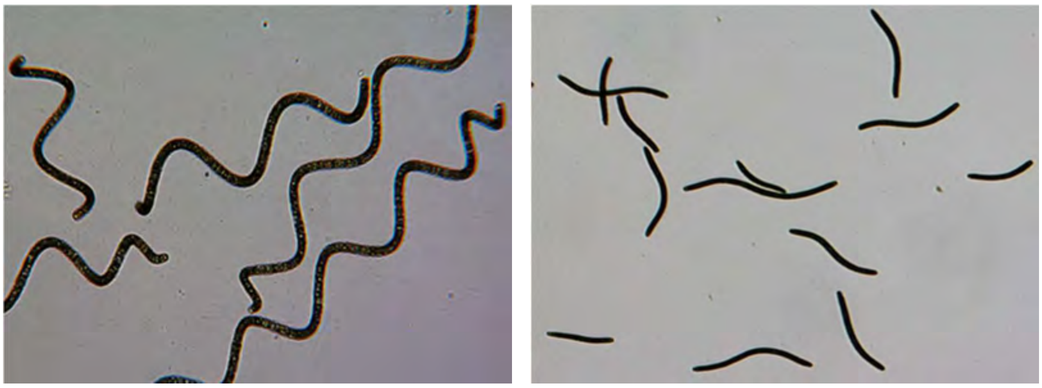


Figure 5-1 S. platensis photos taken under the microscope

5.1.1 The value of *S. platensis*

5.1.1.1 A nutritional food

Historically, *S. platensis* was eaten by Mexican and African people. In the twentieth century, the nutritional benefits were gradually researched and discovered, then *S. platensis* is commercially cultivated as a nutritional supplement. The growing interest in the production of *S. platensis* is due to its special properties such as high digestibility and protein content (51–71% of dry biomass), all essential amino acids, low nucleic acids, methionine, cysteine and lysine [106-108]. Thus, *S. platensis* is helpful to fight hunger and malnutrition in third-world countries. Currently it is cultivated in China, India, Thailand, Japan and the US, etc.

5.1.1.2 Medicinal values

S. platensis is not only nutritious, but also has therapeutic benefits, so it has brought great concern for pharmaceutical industries. Data from preclinical studies demonstrate the hypolipidemic activity of *S. platensis* in various animal models including mouse, rat, hamster, and rabbit [109, 110]. Other studies were carried out to investigating the preventive or protective effects of *S. platensis* on environmental toxicant, heavy metal or drug-induced oxidative stress and inflammation, which clearly demonstrated the antioxidant and anti-inflammatory activities of *S. platensis*. The cardiovascular benefits are primarily resulted from its hypolipidemic, antioxidant, and anti-inflammatory activities [109-114]. Studies on human show that *S. platensis* may also boost the immune system, lower cholesterol, heart health, diabetes treatment, wound healing, improving digestive health, etc. [115, 116].

Phycocyanin is a blue-green color pigment in *S. platensis*. It is used in the pharmaceutical and food industries, and has both antioxidant and anti-inflammatory properties [77, 117].

Although studies in animals performed some good medical properties, more research must be developed on human subjects before *S. platensis* can be recommended for specific medical conditions.

5.1.2 Cultivation of *S. platensis* under PARS

Based on the nutritional and medical values, production of maximum biomass and phycocyanin by *S. platensis* is of great interest. In the natural conditions, *S. platensis* is not able to grow very well because of the bad environmental factors and species invasion. So indoor cultivation has become popular. Especially, LEDs were adopted by many researches to cultivate *S. platensis*. As LED can have a relatively narrow spectrum, combination of different LED may reproduce an optimal spectrum to cultivate *S. platensis* to produce the maximum biomass or specific pigment. That is why LED lighting attracted much attention. According to a study, various light wavelengths and intensity by LEDs were used to find the effects of light on chlorophyll and phycocyanin. The results showed that red spectrum produced the maximum biomass, yellow light produced the most of chlorophyll and blue light developed the best production rates for chlorophyll and phycocyanin [74]. Another paper focused on kinetic parameters and chlorophyll accumulation, and the results showed that chlorophyll content was affected by the LED spectra and followed the order: blue > white > red > green > yellow, whereas protein and lipid accumulation was almost independent of LEDs used [76].

However, each kind of color has a wide range of wavelengths (violet:380-450nm, blue: 450-495nm, green: 495-570nm, yellow: 570-590nm, orange: 590-620nm, red: 620-750nm), as well as various of intensities and operating modes. So relative researches are still necessary to reveal which kind of light is the optimal for *S. platensis* growth or specific biological ingredients. A favorable lighting system cannot only improve the quality and quantity of microalgal biomass, but also save energy and realize ecological development.

5.2 Light requirement for *S. platensis*

In Chapter 4 we found red and blue spectra have the maximum values for PPF, EPPF and phytometric system. However, the light requirements were different between algae and plants due to different physiological characteristics. Not like the average photosynthesizing plants, there is no RQE curve for average algae. Therefore, it is necessary to analyze the light requirement for *S. platensis* and verify the hypothesis through experiments.

Algae have some similar photosynthetic pigments with plants, such as chlorophylls and carotenoids. The action spectrum of photosynthesis has a peak in the blue and red light regions [118, 119]. For actual sunlight, there is about 45% of photosynthetically active radiation (PAR), and only about 20% to 25 % of PAR from the sunlight saturates photosynthesis. In actuality, however, plants do not convert all harvested energy into biomass due to reflection, respiration and solar radiation levels, so an overall photosynthetic efficiency is only 3% to 6% of total solar radiation [105, 120]. Photosynthesizing cyanobacteria have a more significant convention in the global carbon cycle, accounting for 20–30% of Earth's photosynthetic productivity [121]. The capture of light energy for algae through photosynthesis is complex and it is governed by the light quality, quantity, and photoperiod. Besides, the parameters (shape, size, culture surface, etc.) of photobioreactor, the concentration of cell mass, all influence the capture of light photons.

5.2.1 Major pigments in *S. platensis*

Figure 5-2 shows the absorption spectrum of several pigments for cyanobacteria [122]. The main pigments are chlorophyll a, carotenoids and phycobiliproteins. Chlorophyll a absorbs most energy from wavelengths of violet-blue and orange-red light, and reflects green-yellow light. It is an essential photosynthetic pigment in algae and plants because of its role as primary electron donor in the electron transport chain [123, 124]. The carotenoids and phycobiliproteins function as accessory light-harvesting pigments covering regions of the visible spectrum not utilized by chlorophylls. They participate in photoinduced electron transfer processes during photosynthesis – they cannot transfer sunlight energy directly to the photosynthetic pathway, but capture light energy and pass it on to chlorophylls [125-128]. The carotenoid pigments exhibit strong light absorption in the blue portion (400 to 500 nm), including lutein, maximum absorption at 450 nm, cryptoxanthin at 453 nm, and zeaxanthin at 454 nm. Phycobiliproteins combined by phycobilin and protein are specially presented in *S. platensis*, which include phycoerythrin (PE), phycocyanin (PC) and allophyxoxyanin (APC). They are the most important constituents of the phycobilisomes. The peak absorption for chlorophyll a mainly concentrates on the blue (428 to 432 nm) and red (660 to 665 nm) regions. For β-carotene, it is about 450 to 480 nm. For phycoerithrin and phycocyanin, it is about 565 nm and 610 nm, respectively.

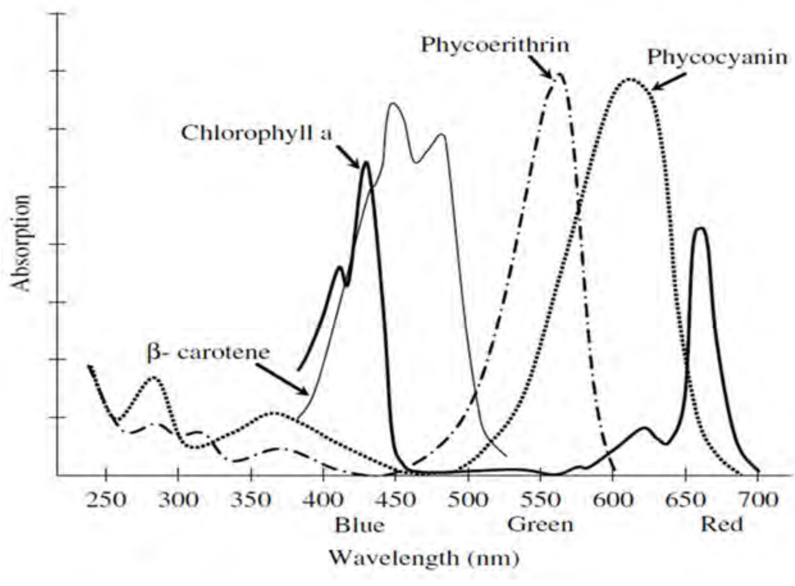


Figure 5-2 Absorption spectrum of several pigments for cyanobacteria

5.2.2 Photosynthesis irradiance (PI) curve

The photosynthesis irradiance (PI) curve, also known as the PE or light response curve, is a graphical representation of the empirical relationship between solar irradiance and photosynthesis (Figure 5-3). In the recent years, the PI curve also applies to microalgae and it has been used extensively to describe the response of algae to light energy [105, 129]. In the figure, R_d is dark respiration; P_{max} is the maximum photosynthetic rate; the initial slope α is the maximum quantum efficiency of photosynthesis when normalized with biomass or chlorophyll a; I_c is the maintenance light energy; I_k is the transition light intensity from light limited to light saturated photosynthesis; and I_i is the light intensity above which photosynthesis is photo-inhibited. The open arrows indicate the high light acclimated response direction and the filled arrows the low light acclimated direction.

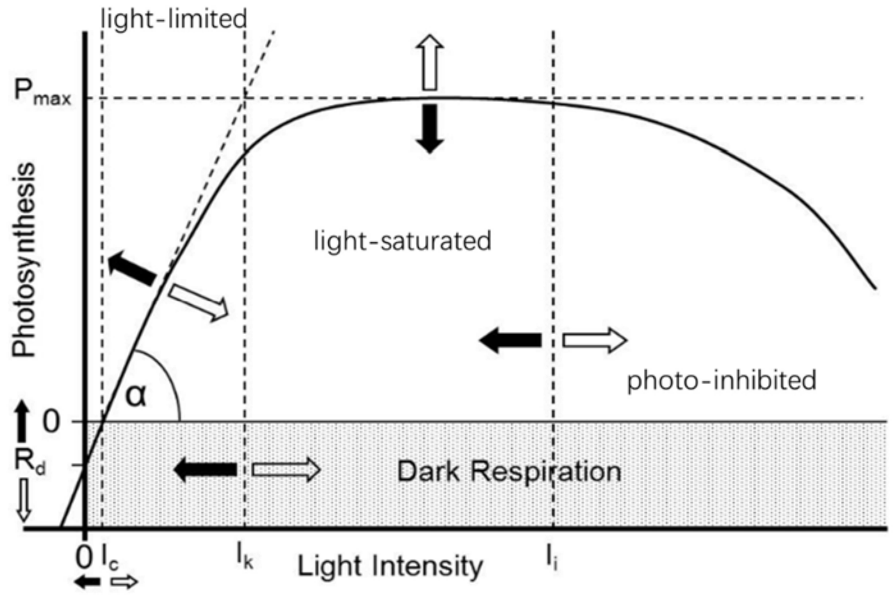


Figure 5-3 The photosynthetic irradiance (P/I) response of microalgae [105, 130]

For the cultivation of *S. platensis*, some key points should be concerned to get the optimal light. There are three regions of light intensity called light-limited, light-saturated, and photo-inhibited regions. Besides, another point is called photo-acclimated. Normally, light saturated region is the best choice and the others should be avoided.

A. Light-limited

Light-limited is an initial region with low light intensities, which means the available light is insufficient. The photosynthetic rates increase with increasing irradiance. As light levels increasing, more ATP (Adenosine Triphosphate) and NADPH (reduced form of Nicotinamide Adenine Dinucleotide Phosphate) in photosynthesis are produced, and the overall rate of photosynthesis increases. In contrast, in a light-saturated region, photosynthetic rates are independent on irradiance.

B. Photo-inhibited

Photo-inhibition is the light-induced depression of photosynthesis when the rate of photon absorption exceeds the rate of electron turnover in PS II [131, 132]. Over the short term, a survival strategy occurs by light-induced photo-inactivation of PS II, whereby the number of redundant PS II units is reduced. Prolonged exposure to high light intensities eventually leads to continuous replacement of the D1 protein and permanent inactivation in PS II [133]. It was reported that a midday depression of dark adapted *S. platensis* as a result of reaction center inactivation caused by photo-inhibition [134]. To repair photo-induced damage, well mixed photic zone and appropriate light intensity are necessary.

C. Photo-acclimated

One of the most important factors influencing photosynthetic rates under continuous or intermittent illumination was whether algae were low or high light acclimated. In this region, photosynthetic rates decrease with an increase in irradiance. In some cases, *S. platensis* would acclimate the illumination strategies for several days until the specific growth rate is constant, after this the test could be more practical and accurate.

5.3 Absorbance of *S. platensis*

5.3.1 Beer's law

When electromagnetic radiation is passed through a sample, some of the radiation is absorbed by the sample. The radiation absorbed by the sample is at particular frequency or of particular frequency range. According to Beer's law, the decrease in the intensity of an incident light beam as it passes through a sample is proportional to the thickness of the material sample and the concentrations of the attenuating species [135]. Understanding the absorbance of *S. platensis* is helpful to find the beneficial spectrum as well as the dry biomass determination. Transmission reference means the transmission of material and medium without *S. platensis* sample. The intensities of outgoing to the incoming radiation I_x/I_0 at specific wavelength can be directly measured. The parameters and formulas that we defined are shown in Table 5-1:

Table 5-1 Parameters and formulas for absorbance

	Symbol	Formula
Transmission reference	I_0	
Transmission	I_x	
Absorption coefficient	K	
Thickness of sample	l	
Absorption	Abp_x	$I_0 \cdot (1 - I_x/I_0)$
Transmittance	T_x	I_x/I_0
Absorbance	A_x	$\lg(I_0/I_x)$ or $K \cdot C_x \cdot l$
Concentration	C_x	$(C_0 \cdot V_0)/(V_0 + V_x)$

Note: V_0: the volume before dilution; V_x: the volume of medium for dilution; C_x: the concentration after dilution

5.3.2 Design of test container for absorbance with monochromatic light

5.3.2.1 Design of test container for absorbance

A. Material selection

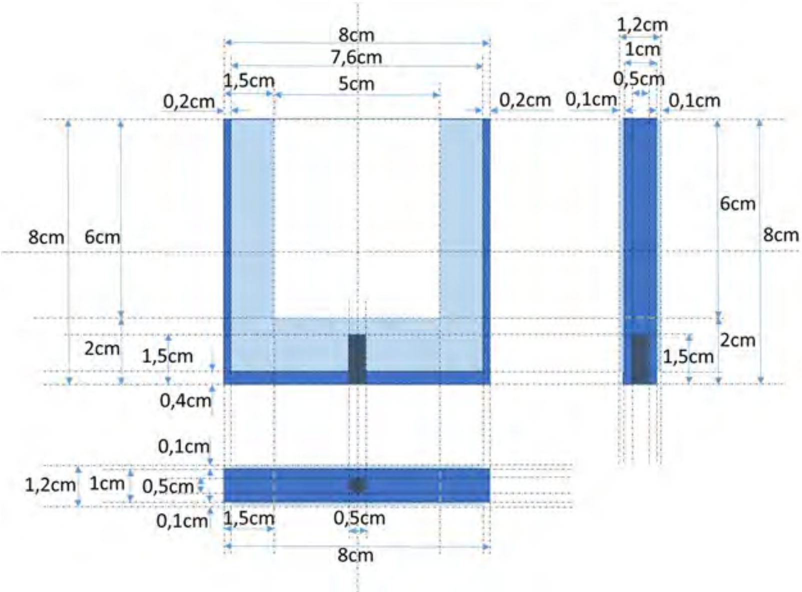
Normal polyvinyl chloride (PVC) material has chlorine, which may be discharged or gasified, and interfere with the biological endocrine (affect reproductive function). Chlorine causes environmental damage at low concentrations and is especially harmful to organisms living in water and soil. So we chose polyoxymethylene (POM) with glass as the container material for *S. platensis*. POM has the advantages of low water absorption, wear-resistant and heat-resistant and good dielectric properties.

B. Glass selection

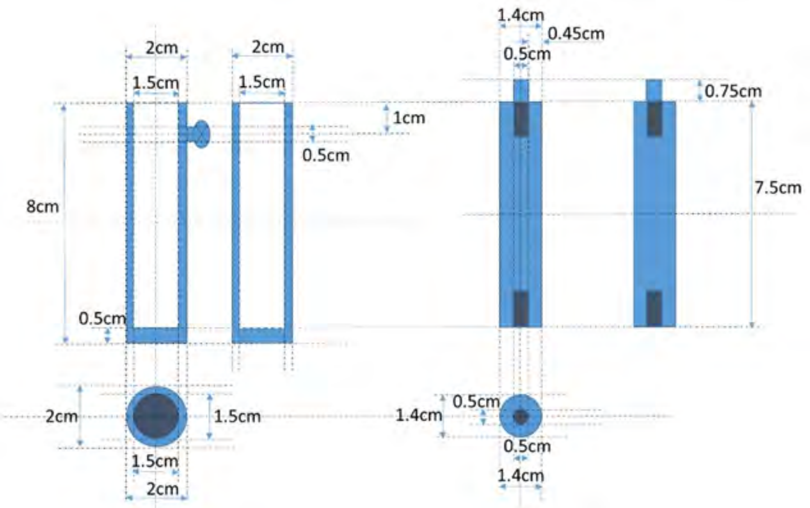
We chose glass of Edmund Optics with high transmittance (96-99％ within 425 to 700nm) and high anti-reflective efficiency (Reflection: ≤0.35％). The size is 3x3 (inch), and 3mm of width.

C. Design structure and dimensions

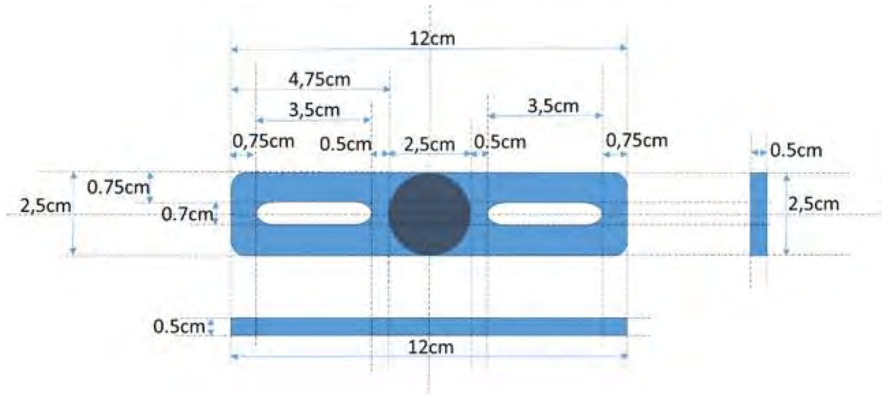
Figure 5-4 shows the structure and dimensions for absorbance measurement. It includes three parts: test container, holder pillar and holder base.



a. Test container



b. Holder pillar



c. Holder base

Figure 5-4 Structure and dimensions for absorbance measurement

5.3.2.2 Test system for absorbance of *S. platensis*

A high resolution (0.1nm) and tunable monochromatic light source on mounting plate (Thermo Oriel: 66901, 69907, 74000) was used for the measurements. Figure 5-5 shows the test system including the monochromator, test container, specbos 1201, PC and software. In order to efficiently analyze the data and figures, a Matlab GUI was programmed (Figure 5-6).

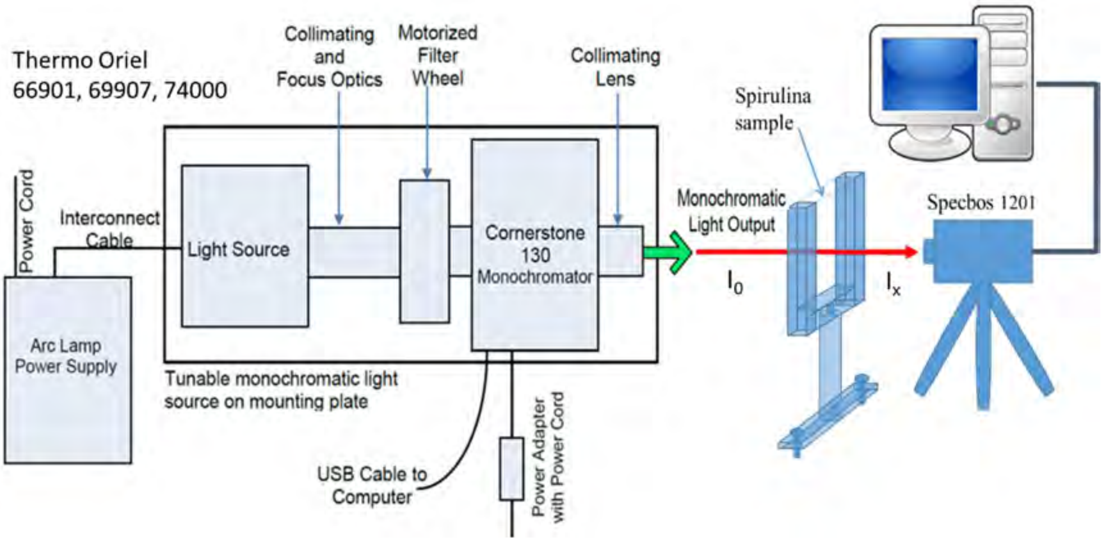


Figure 5-5 The test system for absorbance of S. platensis

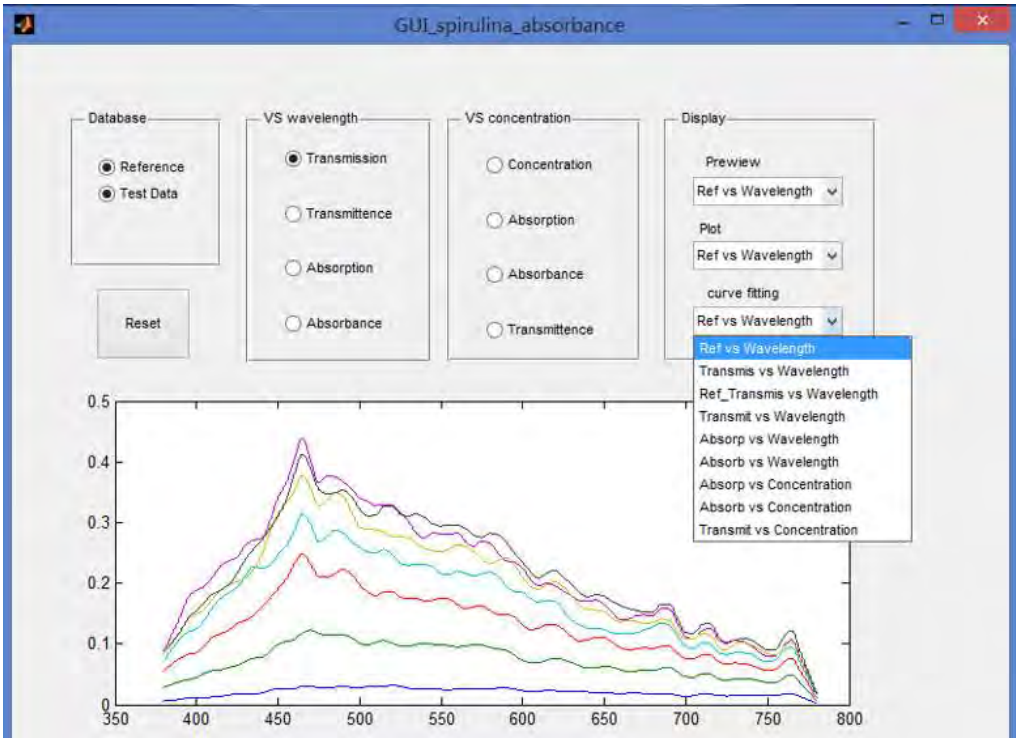
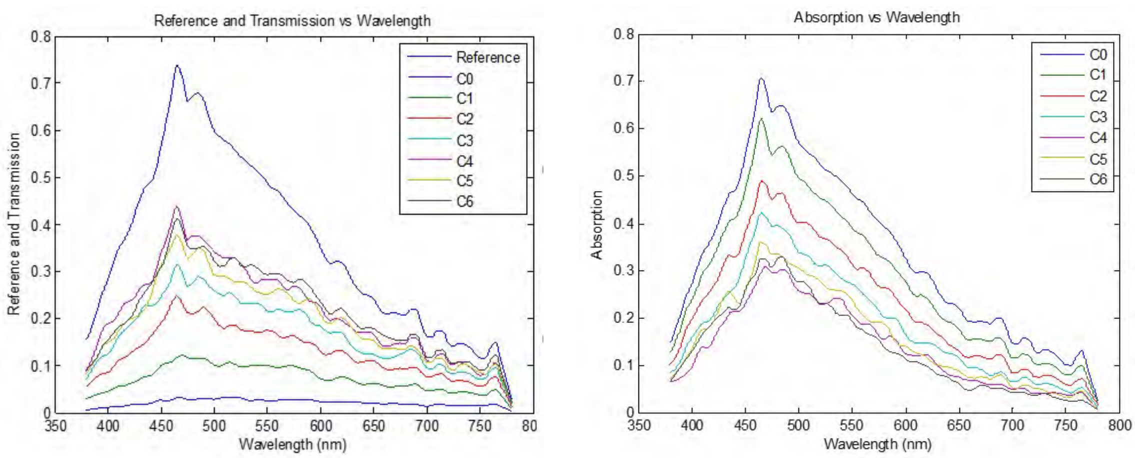


Figure 5-6 Data processing GUI programmed by Matlab

5.3.2.3 Test results for absorbance

In order to well understand the relationship between absorbance, wavelength and concentration, seven different concentrations were tested. From C_0 to C_6, the values are 1, 0.625, 0.455, 0.357, 0.294, 0.238 and 0.217 g/L, respectively. Firstly, we fixed a specific concentration of *S. platensis*, and tested the parameters by wavelength scanning (5nm interval) from 380 to 780nm. Then, we fixed a specific wavelength to find the relationship between the absorbance and concentration. Figure 5-7 presents the relationship between transmission, absorption, transmittance, absorbance and wavelength. The results show that the bigger the concentration is, the lower the transmission and transmittance are, and the higher the absorption and absorbance are. It seems that the absorbance is decreasing with the increasing wavelength. However, it is different to find the optimal wavelength by the results.



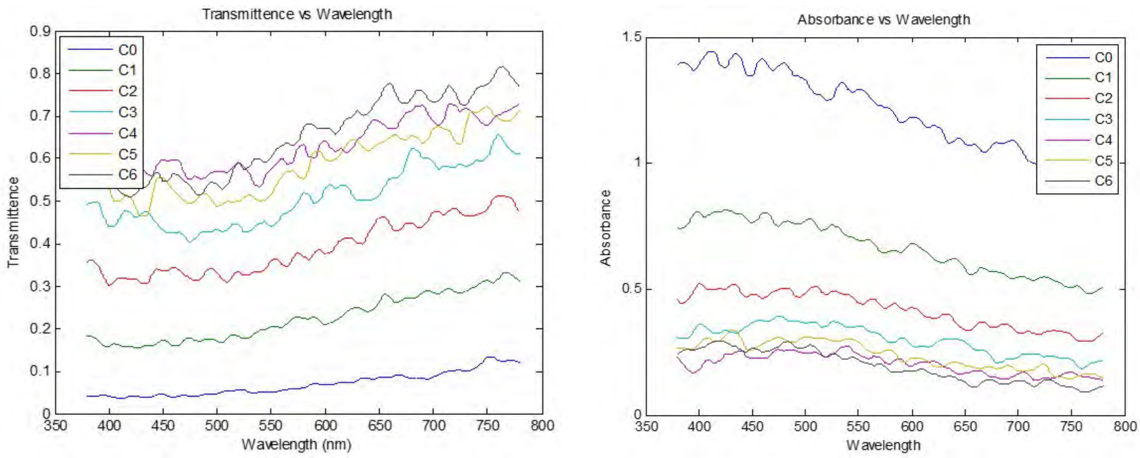


Figure 5-7 The relationship between transmission, absorption, transmittance, absorbance and wavelength

According to Beer's law, the relationship between absorbance and concentration should be linear. We used curve fitting toolbox to verify that, and the results is shown in Figure 5-8. The goodness of linear fitting is acceptable (Table 5-2), so absorbance can be used for biomass determination of *S. platensis*.

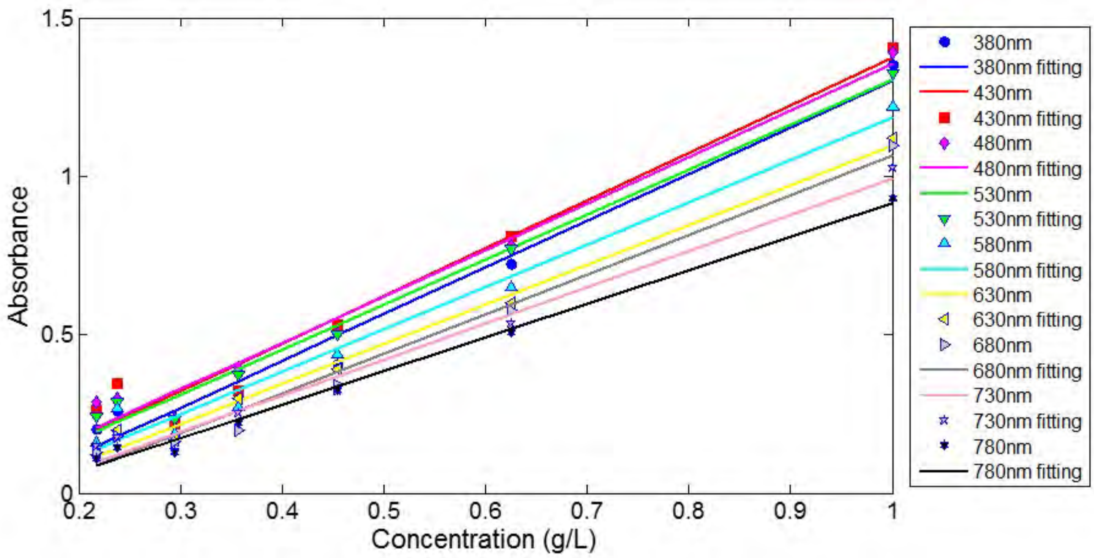


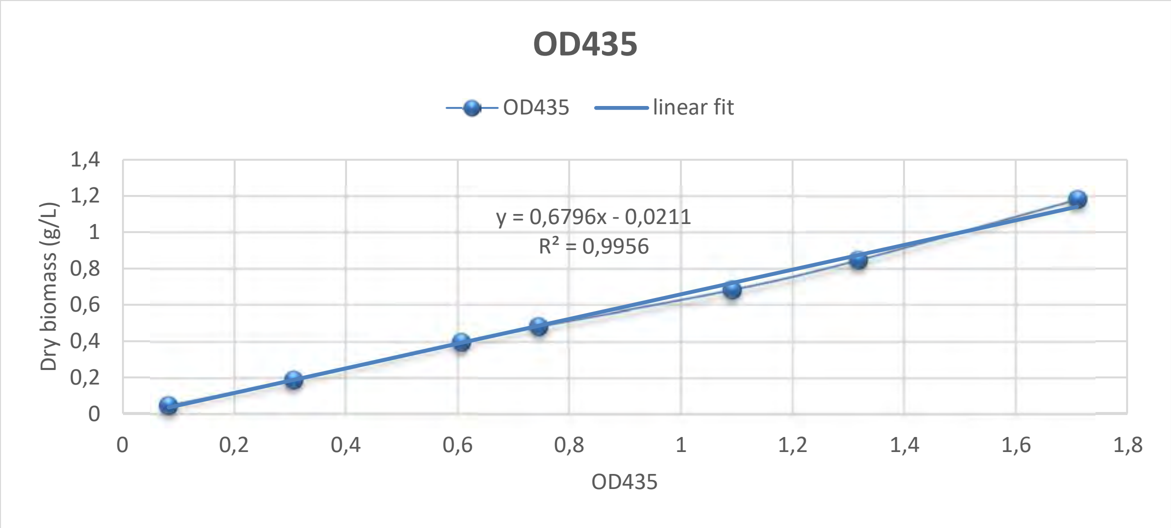
Figure 5-8 Linear fitting for absorbance and concentration

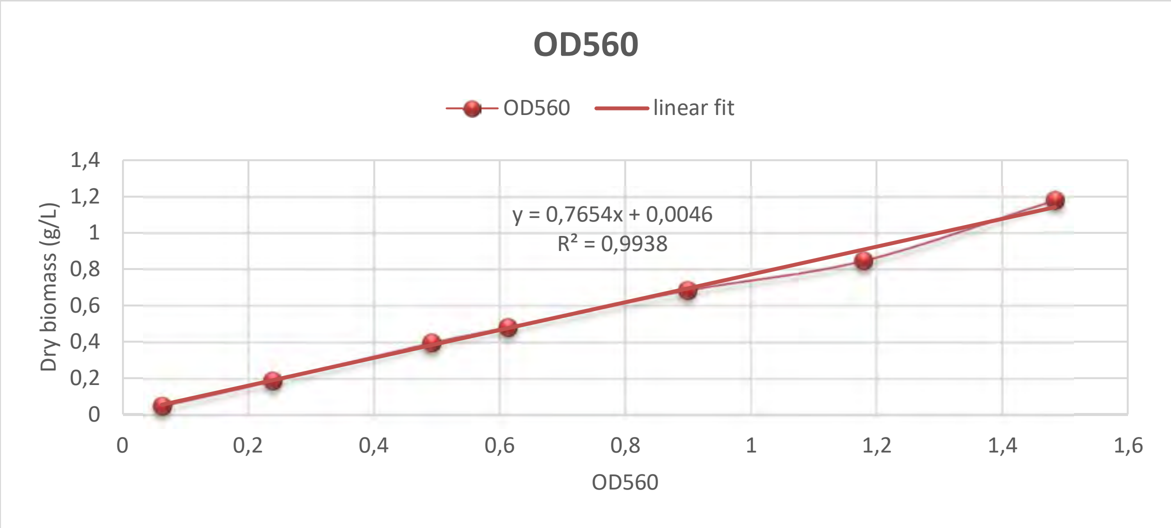
Table 5-2 The goodness of linear fitting for absorbance and concentration

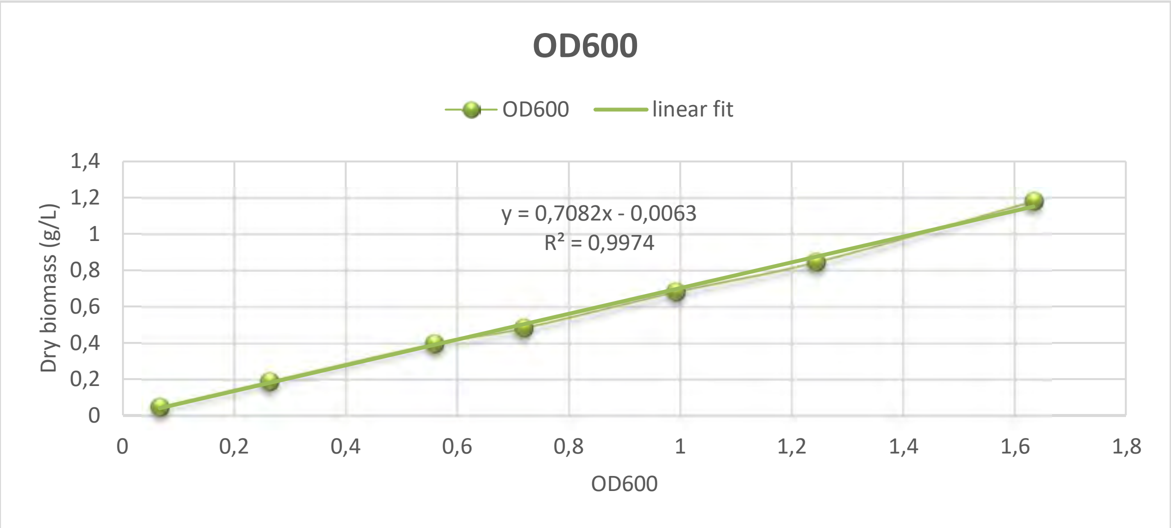
	380 nm	430 nm	480 nm	530 nm	580 nm	630 nm	680 nm	730 nm	780 nm
R^2	0.978	0.9677	0.9785	0.9861	0.9775	0.9903	0.9816	0.9787	0.9923
SSE:	0.0227	0.0352	0.0220	0.0132	0.0191	0.0071	0.0136	0.0132	0.0041
RMSE:	0.0674	0.0839	0.0663	0.0513	0.0618	0.0378	0.0521	0.0513	0.0285

5.3.3 Dry biomass determination

Optical density (OD) at different wavelengths has been widely used to measure algal dry biomass. In order to find out the best wavelength of OD for *S. platensis*, OD435, OD560, OD600 and OD680 were tested by two combined methods: vacuum extraction filtering and serial dilution method. The test results (Figure 5-9) indicate that all the wavelengths are acceptable to be used for OD measurement. OD680 have a best linear fit with R^2 = 0.9992.







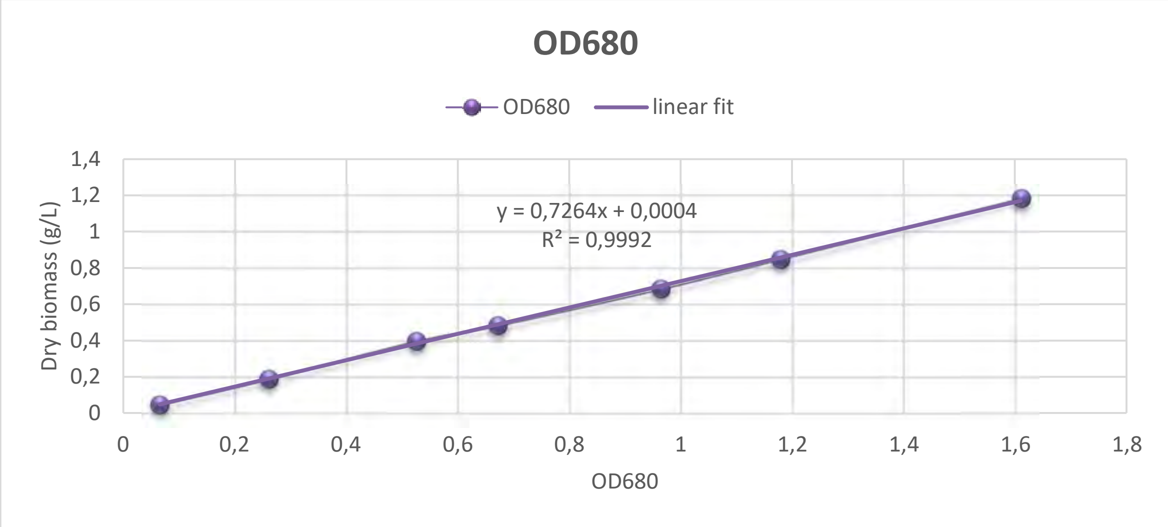


Figure 5-9 Dry biomass determination by OD435, OD560, OD600 and OD680

5.4 Experimental materials and methods

The microorganism used was *Spirulina platensis* UTEX LB 2340 from France, which was grown photoautotrophically in Zarrouk medium [136]. A kind of aquarium made by transparent glass was selected as the incubator. Previous literatures cited the drawbacks of small volume (several hundred milliliters) for cultivation, which may not reflect the real growth and development of algae in practical production. We adopted much bigger size of 15·20·30 cm, and 6 liters of Zarrouk medium were filled for the experiments. As shown in Figure 5-10, two LED plates were fixed beside the incubator with a distance of 1cm to the walls of incubator. The number of LED used is adjustable. It depends on the specific experiments. The experiments carried out in Biosentec company, all the incubators had the same environmental temperature (28℃-35℃). The pH value increased from 8.5 at the beginning to less than 11 at the end of the culture process.

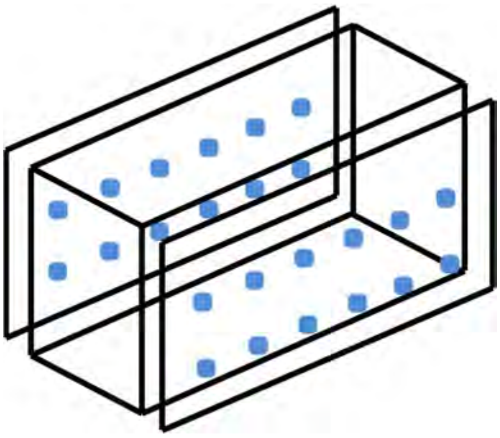


Figure 5-10 The incubator of S. platensis with two LED plates and multi-LEDs

Agitation for *S. platensis* is very important. It is not only for uptaking nutrients and releasing metabolites, but also create a Light/Dark environment, shorten the exposure time allowing above saturating light intensities to be utilized, and ensure an “average” photo-acclimated state of the entire culture [105, 137]. Thus, wave maker pumps are used to agitate the culture solution with a flow velocity of 5000 liters per hour.

According to the absorption spectrum of pigments in Figure 5-2, we tested different colors of LED (Cree and OSRAM) mainly in visible spectrum from 400 to 700nm. LED spectra at 430-460nm, 550nm, 590-620nm, 660nm and 730nm are used for experiments (Figure 5-11), which correspond the peak absorption of β-carotene, phycoerythrin, phycocyanin and Chlorophyll a, respectively. Then single color LEDs and combined colors were adopted for the experiments. Each time we used control variable method and found the more effective spectra for *S. platensis*. Based on the results, we tried some other LEDs with higher efficiencies.

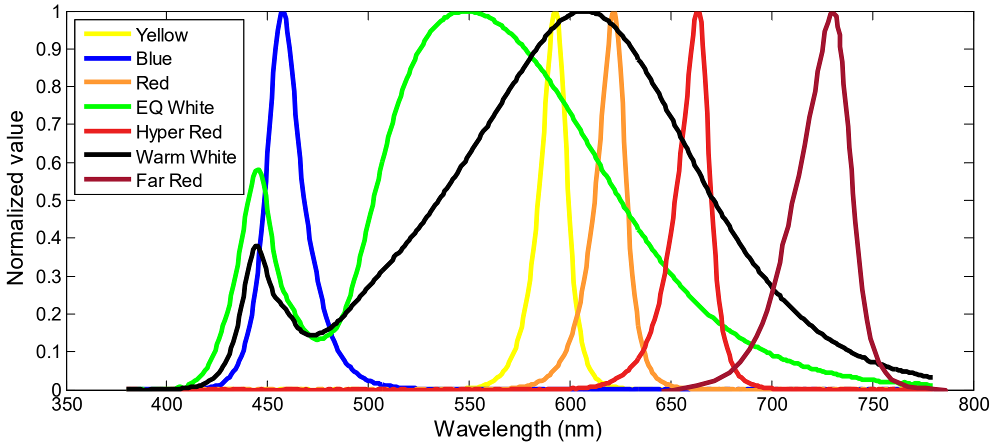


Figure 5-11 LED spectra used for experiments

5.5 Effect of LED spectrum on the growth of *S. platensis*

In this part, several experiments were carried out with different colors, powers and light distributions of LED.

5.5.1 Influence of LED colors

For the first experiment, high power LEDs: blue, red, yellow, white and red/blue ratio at 6/4 were adopted. Each incubator used 36 LEDs, totally 180. Each incubator had the same power. The experimental photos could give an intuitive comparison between no *S. platensis*, initial period and end time, which is shown in Figure 5-12. An incubator with no light was also used as reference. The growth curve shows that red and white light have the absolute predominance for *S. platensis* in the experimental condition. Blue light got the minimum biomass. Without light the *S. platensis* died in the reference.

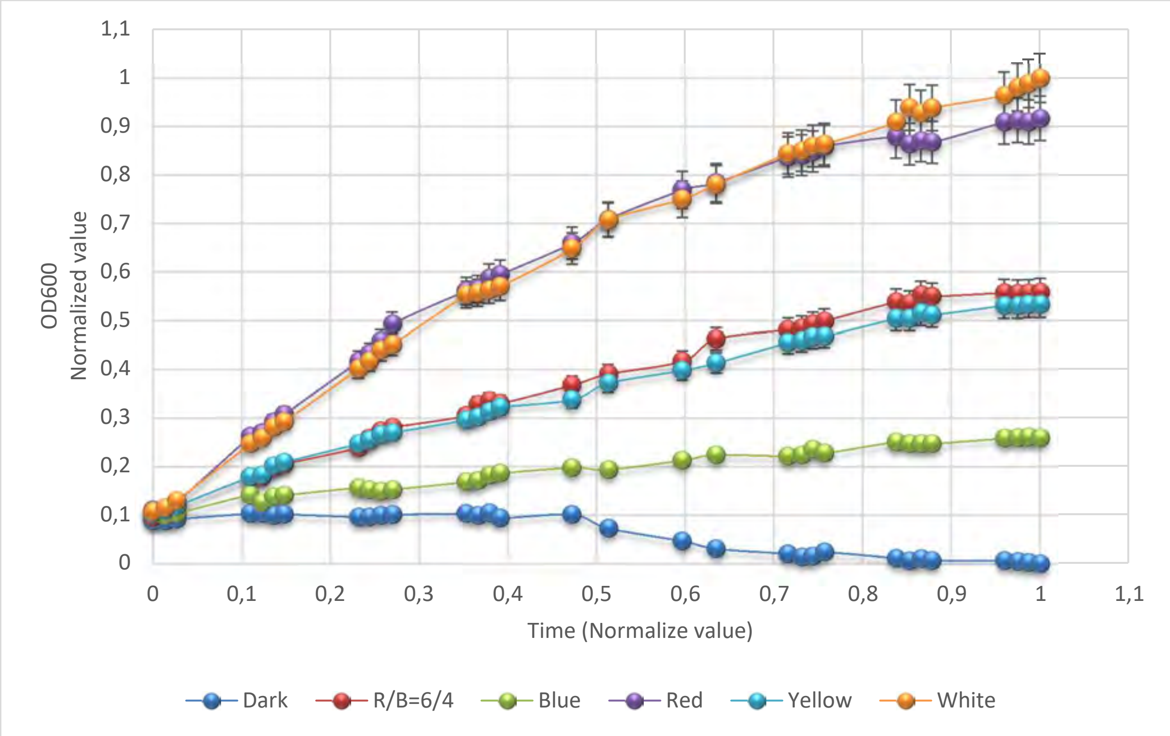
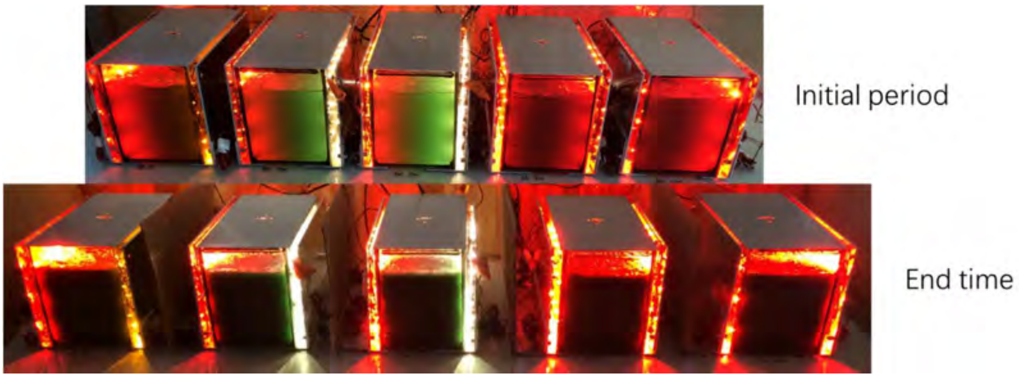


Figure 5-12 Experiment photos and growth curve of S. platensis for the first experiment

5.5.2 Spectrum selection and optimization

Based on the first results, we continued to use the red and white LEDs for the second experiment, combined with yellow LEDs. Different combinations and powers of red-yellow (RY) at 58% of maximum power, red-white (RW) at 58%, red-white (RW) at 83%, red-red (RR) at 58% (as reference), and red-red (RR) at 100% were compared (Figure 5-13). The actual results indicate that overall productivity had a significant increase compared with the first experiment. All the incubators had the normalized final OD600 > 0.6. RY 58% had a minimum final OD600 at about 0.63. The best performance was RW 83% with a final OD600 at about 1. RW 58% was not as good as RR 58%, which means the red and white LED combination has a relative lower photosynthetic efficiency than single red LEDs with the same power. RR 100% was not the best one, maybe due to the photo-inhibited effect caused by too high light intensity.



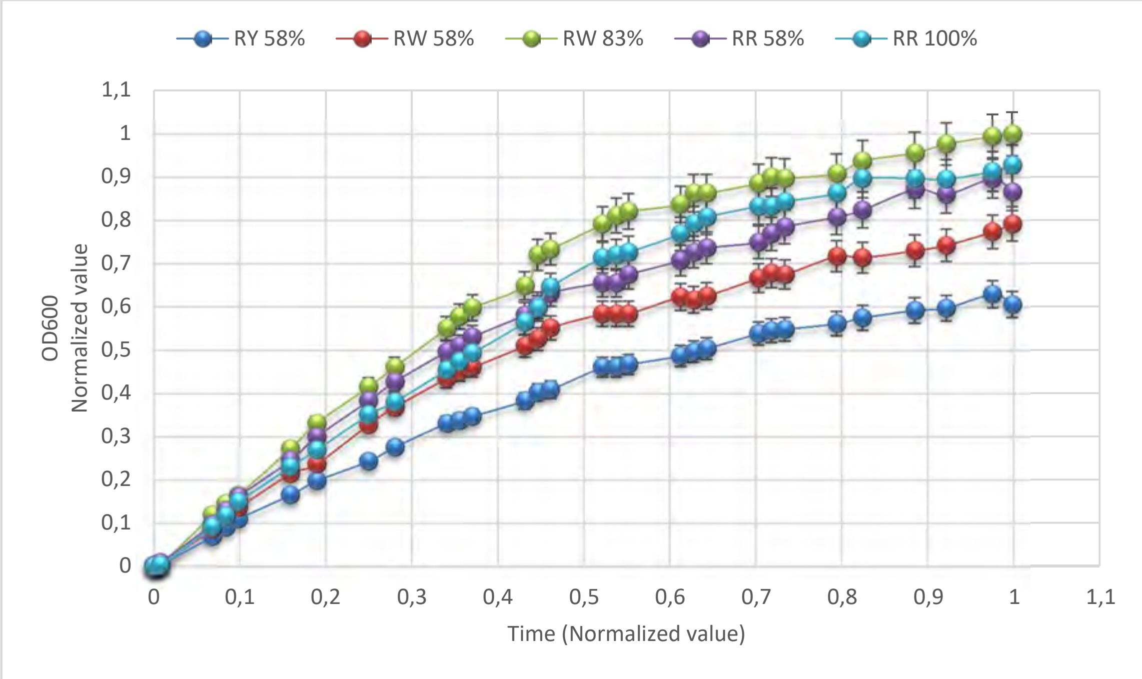
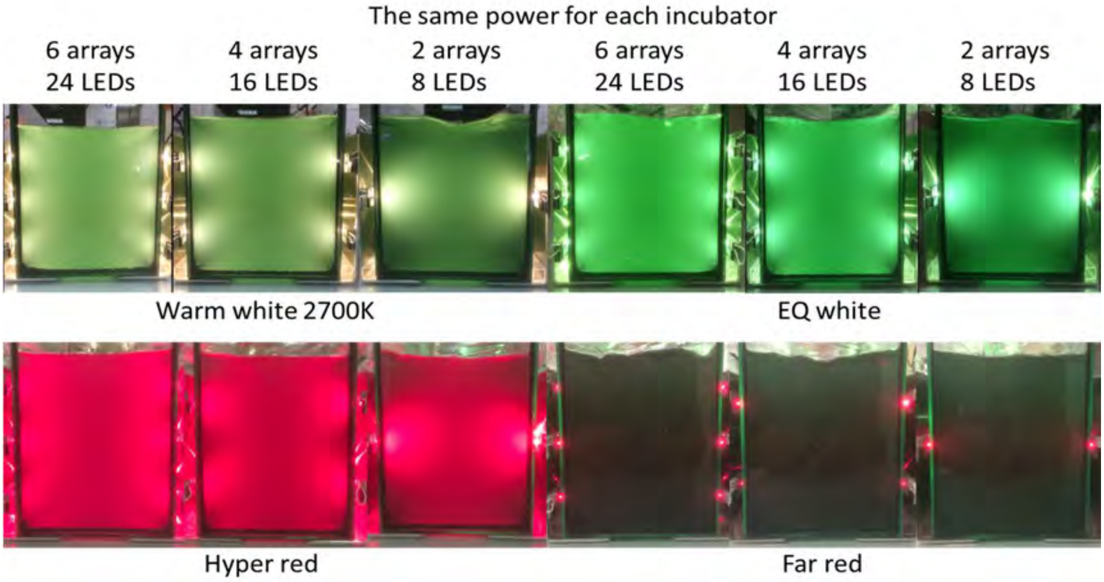


Figure 5-13 Experiment photos and growth curve of S. platensis for the second experiment

5.5.3 Optimization LED efficiency and distribution

In order to identify which is better for *S. platensis* between red and white LEDs, we adopted four new spectra of LEDs with higher efficiency: hyper red (HR), warm white 2700K (W2700K) and EQ-white (EQW). Far red (FR) was also used for comparison. The environmental conditions were the same compared to the previous experiments except the distribution of LEDs. For each color, we adopted 3 different patterns: 6 arrays with 24 LEDs, 4 arrays with 16 LEDs, and 2 arrays with 8 LEDs. In order to know the effects of environment, an incubator without LED light was set as a reference. According to the test result of LED spectral characteristics, we assumed that the light intensity has a linear relationship with the power of LEDs, and each incubator used the same power. Figure 5-14 shows the experiment photos and growth curve of *S. platensis*.

The results show that far red spectrum almost has no effect on the growth of *S. platensis*, similar with the dark reference. That is because there is no active spectrum within PAR from 400 to 700nm. Hyper red performed the best in all the LED distributions. With the same power, HR 24 LED was better than HR 16 and HR 8. This can be explained by more uniform spectral distribution created by 24 LEDs on the surface of incubator. EQW 24 and EQW 16 had the similar results, and they produced more *S. platensis* than EQW 8. The group of W2700K had abnormal results. W2700K 16 was the best, W2700K 24 and 8 had the similar production. However, we can get the conclusion that hyper red could be the optimal spectrum for cultivation of *S. platensis* in the test conditions.



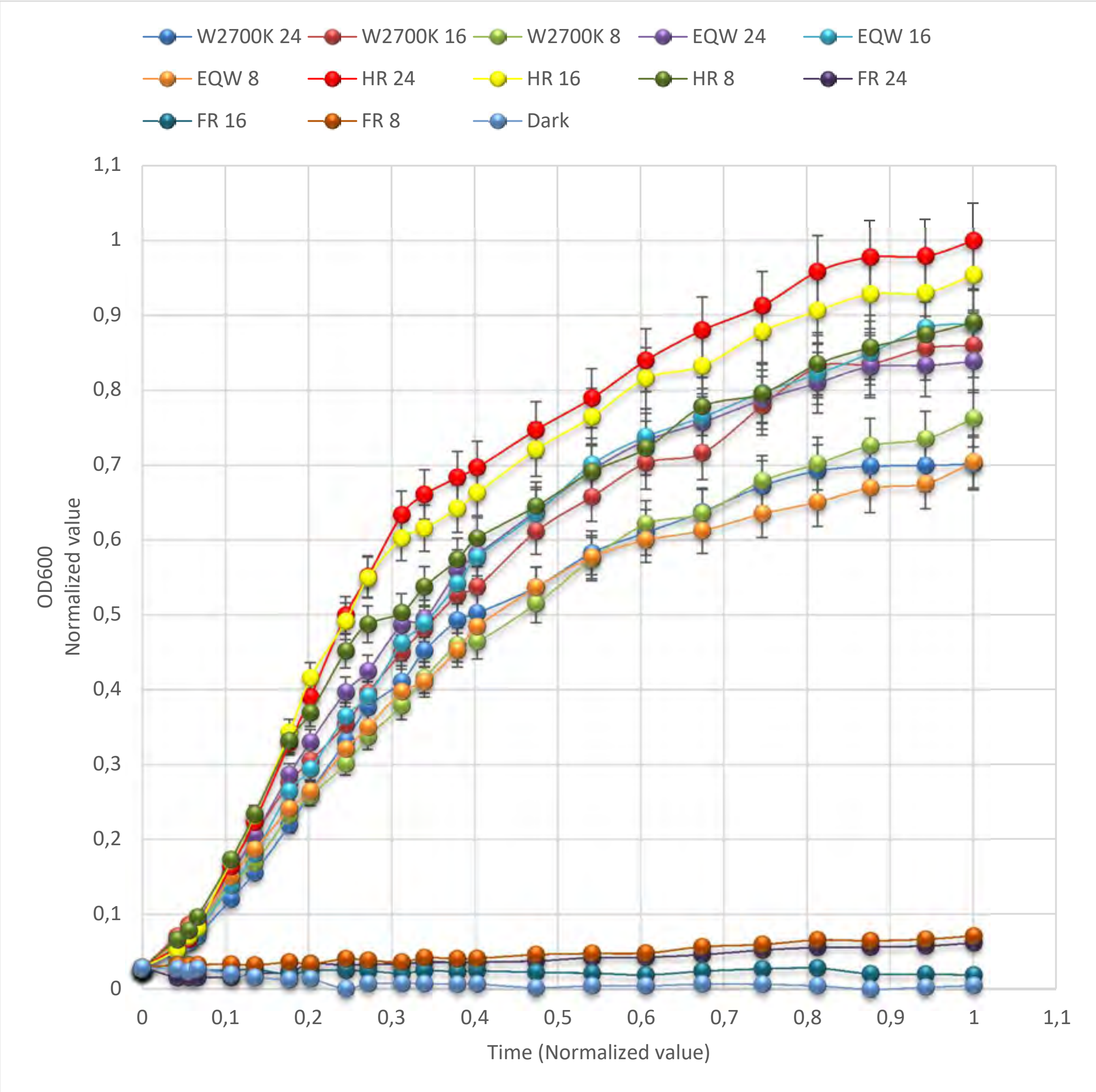


Figure 5-14 Experiment photos and growth curve of S. platensis for the third experiment

5.5.4 Optimization of light intensity

Eight power levels were used for the incubators. The ratios of maximum power are 0, 10%, 20%, 35%, 50%, 65%, 80% and 100%. Although HR 24 performed the best result, there were not large differences between HR 24, 16 and 8, then we used 8 hyper red LEDs for each incubator, which could also reduce the LED cost. From the power, the corresponding light intensity can be known according to the experimental data of LED characteristics. Figure 5-15 shows the growth curve of *S. platensis* for the experiment.

At the beginning, the specific growth rate was not the maximum because of photo-acclimation. The microalgae will acclimate during the production cycle in batch cultures, being high light acclimated soon after inoculation of a new culture, to low-light acclimated at the end of the batch process when the cell density is high [138]. The *S. platensis* was taken from an 80L incubator with white fluorescent lamps, which has a white light and low light intensity acclimated. When a red and higher intensity light suddenly happened, the *S. platensis* could not adapt the new environment and have a photo-acclimated response. Thus, the maximum growth rate happened several hours later.

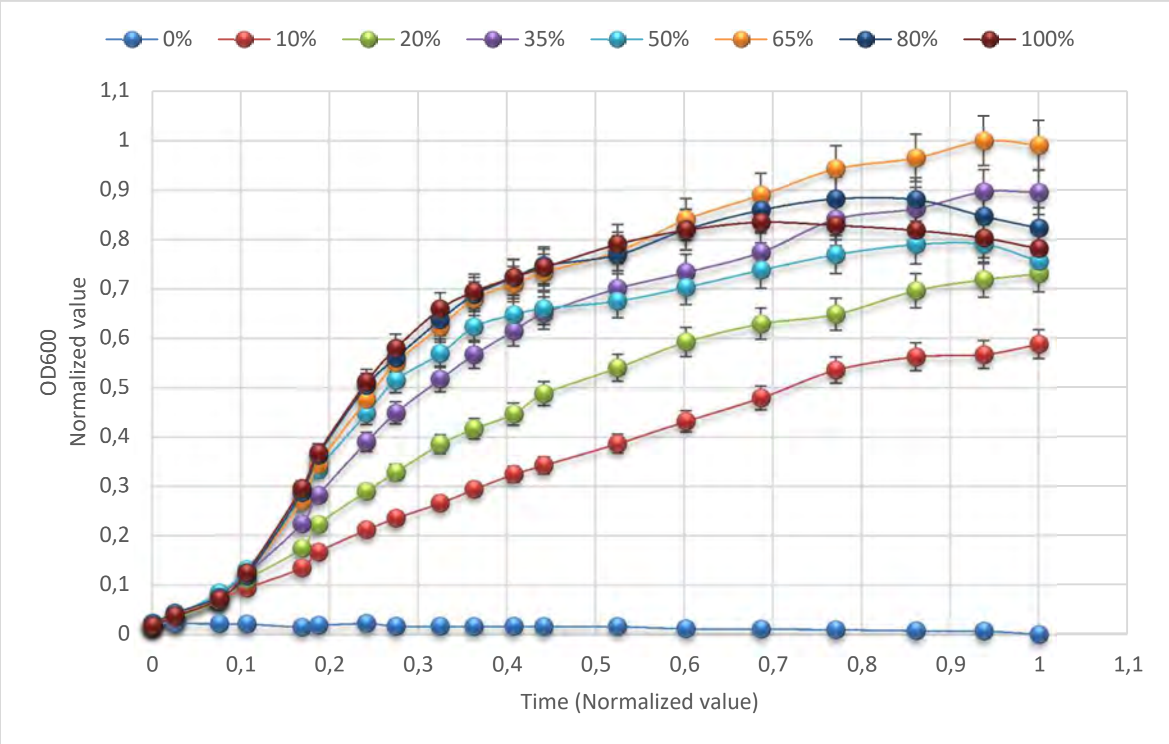


Figure 5-15 Growth curve of S. platensis for the fourth experiment

From the normalized time of 0.1 to 0.45, the production of *S. platensis* was increasing with the increasing power. The saturated light point seems between 50% and 65% maximum power, because no more increase for a higher light power. The incubator of 50% maximum power showed an incoherent behavior. The growth curve was abnormally smaller than 35% maximum power. The reason was probably a man-made contamination of Zarrouk medium caused by the measurement, or environmental factors. However, the other incubators presented expected results. At the normalized time of 0.7 and 0.8, the growth curve at 100% and 80% began to drop respectively. It is reasonable to consider photo-inhibition to be a main reason in the surface layers of the medium. From 10% to 65% maximum power, the growth curve gradually flattened out with the time. With increasing power, a higher production of *S. platensis* was obtained. This results to higher opacity of the cell compared to low power illuminated one, and therefore a lower average photon flux for each cell.

5.6 Effect of intermittent light

5.6.1 Intermittent light

Intermittent light, also called pulse light, has been used as a special light regime to increase specific growth rate and photosynthetic rate [139, 140]. What we should know is that the optimal spectrum for plant growth is not constant, and it will change with growth stages of plants. Some papers also show that pulse and intermittent light can promote more photosynthesis, and save more energy [141, 142]. The increasing productivities with light/dark (L/D) cycles could be explained by electron turnover rates in photosynthesis. If the L/D frequencies match the turnover rates, photosynthetic efficiencies would be at their highest. Intermittent light regime was tested using the dynamic LED lighting system we designed (Chapter 3). It allows us to study dynamic light effects onto plant's growth.

There are many patterns for intermittent light.

A. Continuous illumination

The ingoing photon flux density (PFD_{in}) can be different, but the PFD_{in} or transmission light (I_{out}) will be constant in one culture (Figure 5-16).

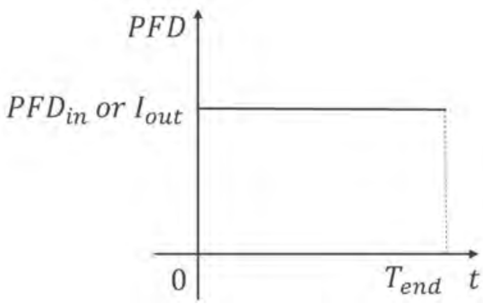


Figure 5-16 Continuous illumination

B. Intermittent illumination

In the intermittent illumination (Figure 5-17) we define some parameters such as light period (T_l), dark period (T_d), light/dark cycle (T_c), light frequency (f), and light fraction (ε), where $\varepsilon = \frac{T_l}{T_c}, 0 < \varepsilon < 1$.

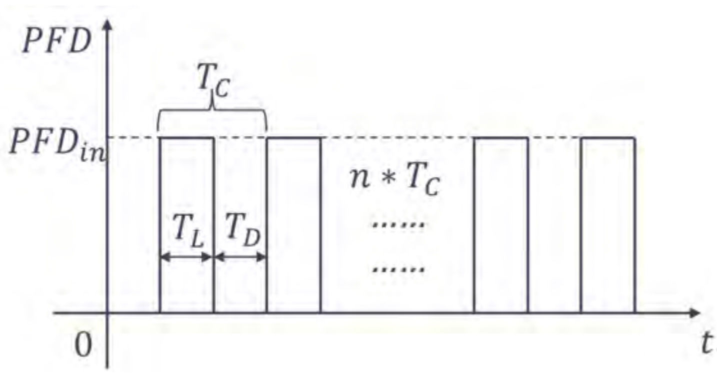
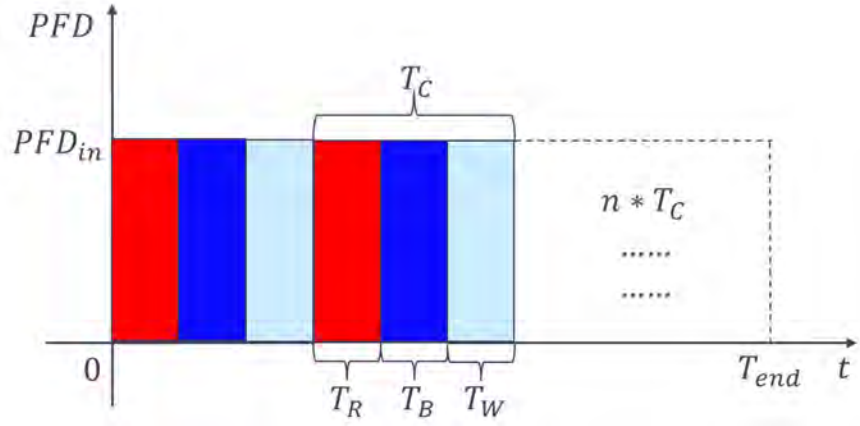


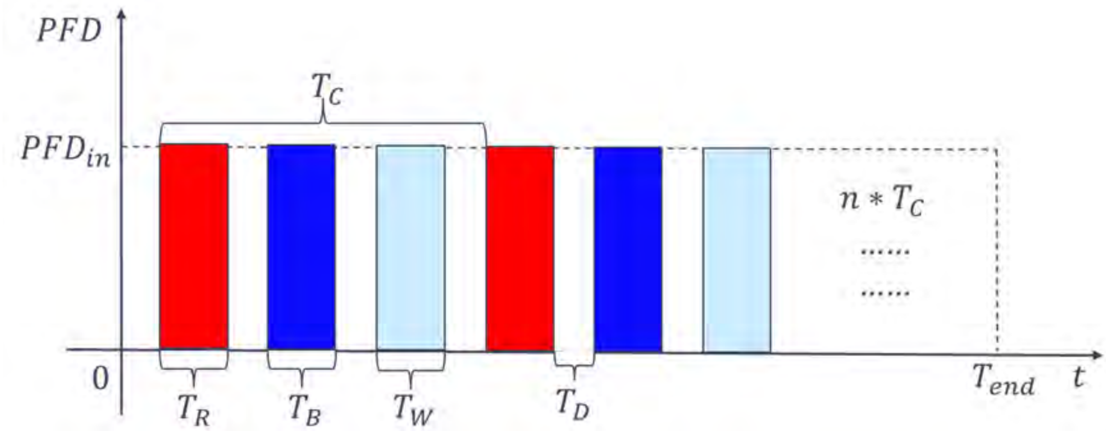
Figure 5-17 Intermittent illumination

C. Alternating illumination

It includes equal intervals and continuous illumination ($T_R = T_B = T_W$), and unequal intervals and continuous illumination ($T_R \neq T_B \neq T_W$) (Figure 5-18 (a)). T_R, T_B and T_W is the time of light up for red, blue and white LED, respectively. If the illumination is not continuous, it can be called equal interval and intermittent illumination, and unequal intervals and intermittent illumination (Figure 5-18 (b)).



(a)



(b)

Figure 5-18 Alternating illumination

5.6.2 Experimental result under intermittent light

The red and white LEDs was adopted for different intermittent light patterns: red-red (RR) 1000 Hz, red-red (RR) 100 Hz, red-red (RR) 25 Hz, white-white (WW) 1000 Hz, and red-red (RR) continuous light used as a reference. The test results are shown in Figure 5-19. Surprisingly, almost no changes were observed on the growth curves for all incubators, ignoring inevitable errors.

However, the unexpected results can be explained as follows. For many decades, the enhancement of photosynthesis in intermittent light was interpreted by light reaction and dark reaction, which means that light energy is captured during the light time and then utilized in the dark until the next light flash is received [105]. This alternative biological mechanism can enhance photosynthesis. But implementation of this mechanism requires special conditions. The time-scales for electron turnover rates in PSII and PSI range from femtoseconds to milliseconds [143]. The L/D frequencies in the experiment was too low to match the turnover rates in photosynthesis. However, much higher L/D frequencies give a great challenge to the electronic components. Besides, higher costs of drivers or photo-bioreactors are inescapable.

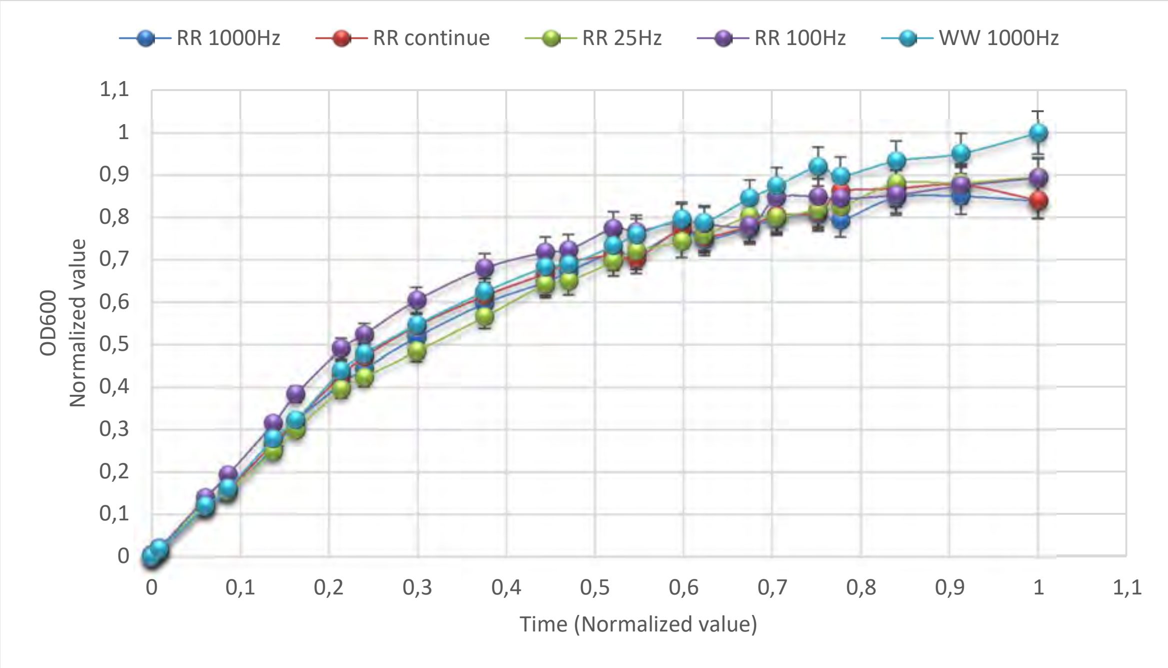


Figure 5-19 Growth curve of S. platensis for the third experiment

5.7 Effect of red and blue LEDs on the production of phycocyanin by *Spirulina platensis*

5.7.1 Introduction

Phycocyanin (PC) is a photosynthetic pigment, which falls into C and R types. The former was found in cyanobacteria, and the latter was found in red algae and cryptophytes. PC is an accessory pigment to chlorophyll, which appears blue, absorbs orange and red light, and transmits light energy during the process of photosynthesis. Over the past decades, PC has been used as natural edible pigment, cosmetics, medicine and fluorescent reagent. Until now, its new functions such as antitumor, antioxidant, anti-allergy and improving the organism immunity are being gradually explored.

PAR between 400-700nm has the dominant role for photosynthesis driven by photons rather than light energy. PAR includes photosynthetic photon flux (PPF) and yield photon flux (YPF) [93]. YPF is a more accurate measure of a horticulture light ability to drive photosynthesis of plants. In this part, PPF was used to measure the light intensity for cultivating *S. platensis*.

It has been clarified that blue and red light are the most important spectra for plant photosynthesis, but this mechanism may not apply for microalgae. PC has much higher content than other pigments and it is indispensable for photosynthesis in *S. platensis*, but the functions of light on the production of PC are seldom reported.

In this part, we used five different proportions of blue and red photons to cultivate *S. platensis* in order to explore the effects of specific spectrum on the production of PC. The experimental design methods are described and analyzed in the second part. The results are presented and discussed in the third part.

5.7.2 Materials and Methods

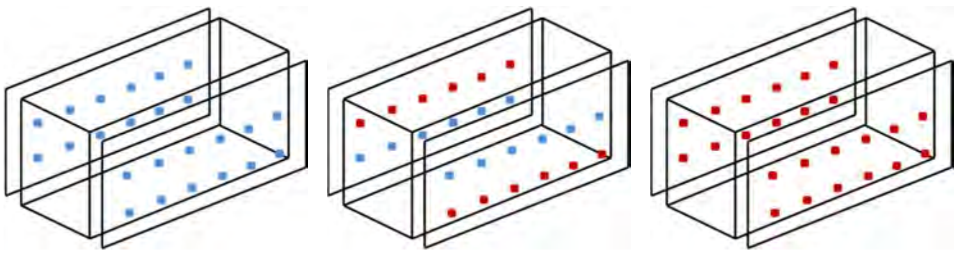
5.7.2.1 Culture conditions for phycocyanin

The microorganism used was *Spirulina platensis* UTEX LB 2340 from France, which was grown photoautotrophically in Zarrouk medium [136]. The strain culture was grown in 80 litres of glass container with continuous illumination provided by white tubular fluorescent lamps at 32.5±1℃, and agitated by a circulating pump. For inoculation, we took certain amount of the strain culture, and filtered it by 30μm strainer, then diluted the *S. platensis* with Zarrouk to OD600=0.18.

The experiment was performed in greenhouse with air conditioner. The temperature of culture medium was controlled at 32.5±0.5℃. Wave maker pumps are used to agitate the culture solution. The flow velocity was 5000l/h. The pH value increased from the beginning of 8.5 to the end of less than 11 during the culture process.

Blue and red LEDs were selected with the same model and configuration. The peak wavelengths were 458nm and 625nm, and viewing angle 135º and 130º at 50% current value, respectively. Both of the LEDs had the rated power of 1 watt and maximum current 1A.

A kind of aquarium made by transparent glass was selected as the incubator. The size is 15·20·30cm, and 6 liters of Zarrouk medium were filled for the cultivation. As shown in Figure 5-20, two LED plates were fixed beside the incubator with a distance of 1cm to the walls of incubator. Twenty-four LEDs were adopted for each incubator, and evenly distributed on both sides. The PAR of each incubator was 74.42 $\mu mol \cdot m^{-2} \cdot s^{-1}$ tested by Specbos 1201 in the integrating sphere (diameter: 25cm). The accurate PAR function is available in section 2.3.2. Five different proportions of red and blue photons are set as 4:0, 3:1, 2:2, 1:3 and 0:4, respectively.



(a) B:R=4:0 (b) B:R=3:1, 2:2 and 1:3 (c) B:R=0:4

Figure 5-20 Experimental setup for incubators with five different proportions of red and blue photons

5.7.2.2 Phycocyanin content detection

Certain amount of dry *S. platensis* sample was dissolved by phosphate buffer solution (pH=7), shattered by the ultrasonic wave, and placed in the refrigerator (-20℃) for 12 hours to precipitate out PC, then centrifuged 15min at 3000 rpm. The supernatant was used to measure the absorbance at 620nm, 652nm and 562nm by spectrophotometry. The functions for the mass fraction of phycocyanin (MFPC) are as follows [144]:

$$X_1 = 0.187 \cdot A_{620} - 0.089 \cdot A_{652} \quad 19.$$

$$X_2 = 0.196 \cdot A_{652} - 0.041 \cdot A_{620} \quad 20.$$

$$X_3 = 0.104 \cdot A_{562} - 0.251 \cdot X_1 - 0.088 \cdot X_2 \quad 21.$$

$$X_4 = (X_1 + X_2 + X_3) \cdot \mathrm{V} \cdot 100/(\mathrm{m} \cdot 1000) \quad 22.$$

Where: X_1 is the content of PC in mg/mL^{-1}; X_2 is the content of allophycocyanin (in mg/mL^{-1}); X_3 is the content of phycoerythrobilin (in mg/mL^{-1}); X_4 is the mass fraction of PC (g/100g); A is the absorbance of corresponding wavelengths (620nm, 652nm and 562nm); V is the constant volume of test samples (ml); m is the dry weight (g) of test samples.

5.7.3 Results and discussion

5.7.3.1 Growth curve of S. platensis

The experiment was conducted in a controlled environment (Figure 5-21). After 5 days of continuous illumination we got the growth curves of *S. platensis* in Figure 5-22. The specific growth rate under red LEDs was much faster than blue. OD600 increased from 0.18 to 1.324, about 7.4 times the original. The second one was B:R=2:2 of OD600=1.031. B:R of 3:1 and 1:3 almost had the same growth rate. Blue light got the minimum biomass, and OD600 was only twice the original. The results, consistent with previous experiments, indicate that red light is the most conducive to photosynthesis in the experimental conditions, which yields the largest biomass of *S. platensis*. The combinations of red and blue LEDs have an intermediate effect for photosynthesis. Blue light does not perform well for that.

Figure 5-21 The experiment conducted in a controlled environment for phycocyanin

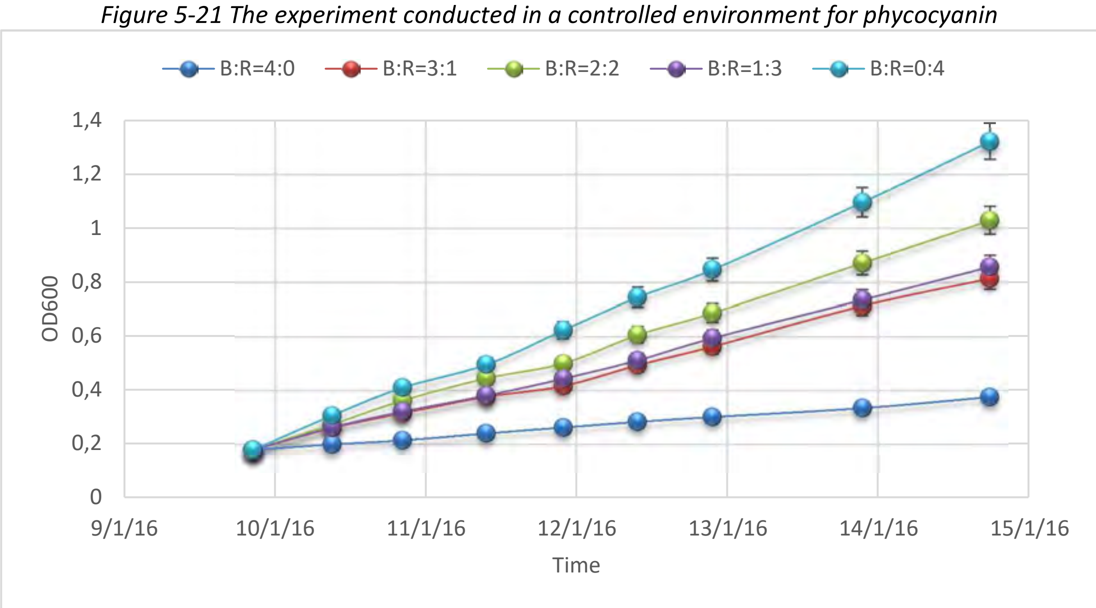


Figure 5-22 Growth curves of S. platensis for phycocyanin

5.7.3.2 Mass fraction of phycocyanin

The experiment was repeated three times. For the second and third times we inoculated with the parental generations of each incubator. The other conditions remained the same. The test data and results for MFPC are shown in Table 5-3 and Figure 5-23. MFPC under TFL (Tubular Fluorescent Lamp) was used as a reference. It shows that the maximum average MFPC under blue light is about 2.3 times of that under red light. The average MFPC decreased with the increase of red light. But the average MFPC under B:R=2:2, 1:3 and 0:4 did not show much difference. Under red light, the biomass increased very quickly, which has a higher priority to obtain more nitrogen source. However, PC serving as alternative nitrogen storage, the slow growth of *S. platensis* is more suitable for PC synthesis under blue light [73].

Compared with the second and third generations, MFPC of the first generation was the lowest under blue and combinations of blue and red light. MFPC of the second and third generations had the same trend to increase excepted with red light where the third generation has a lower MFPC. It can be inferred that blue light promote the MFPC in different generations. But MFPC does not show that trend under the red light.

The total average production of PC (TPPC) is shown in Figure 5-24. Although blue light is conducive to produce PC, TPPC is only 66.4% of that under red light. B:R=3:1 and red light could be better choices to produce more PC.

Table 5-3 Test data for mass fraction of phycocyanin in the experiment

	A_{562}	A_{620}	A_{652}	X_1	X_2	X_3	X_4 (%)
B:R=4：0	0.952	1.839	0.789	0.274	0.079	0.023	31.355
B:R=3：1	0.657	1.292	0.581	0.190	0.061	0.015	22.175
B:R=2：2	0.412	0.797	0.378	0.115	0.041	0.010	13.921
B:R=1：3	0.393	0.761	0.371	0.109	0.042	0.010	13.383
B:R=0：4	0.488	0.954	0.449	0.138	0.049	0.012	16.586
TFL	0.622	1.213	0.518	0.181	0.052	0.015	20.608

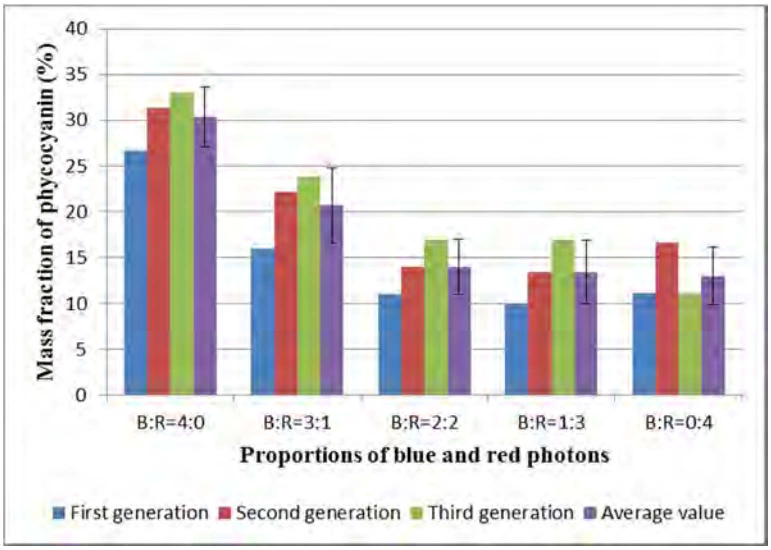


Figure 5-23 Mass fraction of phycocyanin under different proportions of red and blue photons in three generations

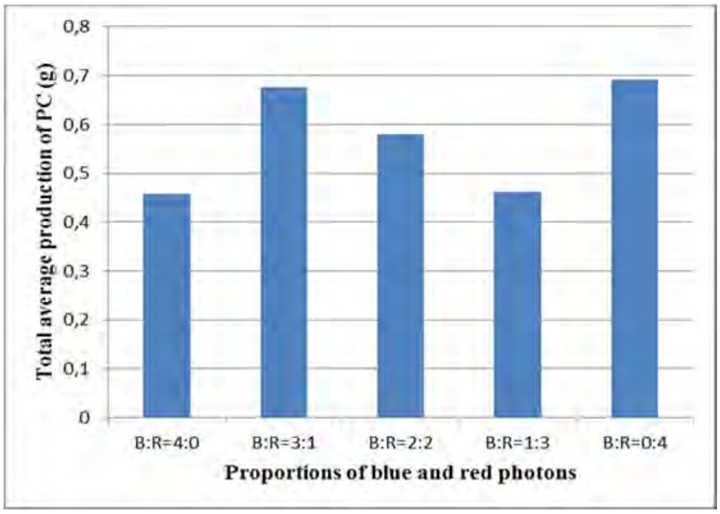


Figure 5-24 Total average production of PC per incubator in three generations

5.8 Spirulina growth modeling

In this part, mathematical analysis was presented to characterize *spirulina* growth and get the maximum economic efficiency. Because of limited time and space, we only analyzed the mathematical models for the optimized spectrum of LED in session 5.5.4.

5.8.1 Modified Monod model for specific growth rate

The Monod equation is an empirical model for the growth of microalgae. Originally it was proposed to relate microbial growth rates to the concentration of a limiting nutrient [145, 146]. Recently, it has also been used to describe the light effects on the growth of microalgae. *S. platensis* was growing in an exponential phase in a specific range according to previous investigation. In order to investigate growth characteristics of *S. platensis*, the specific growth rate (μ) was determined by equation 23.. Then, a modified Monod model was proposed to depict the relationship between different light intensities and the algal specific growth rate (equation 24.) [75].

$$\mu = \frac{lnCDW_1 - lnCDW_0}{t_1 - t_0} \quad 23.$$

$$\mu - \mu_0 = \frac{\mu_{max}(E-E_0)}{K_s+(E-E_0)} \qquad 24.$$

Where CDW_1 is the cell dry weight at time t_1, CDW_0 is the cell dry weight at time t_0, μ_{max} is the maximum specific growth rate, and E is the light intensity of LED. K_s is the Monod constant to imply the light intensity needed for *S. platensis* to reach half of the maximum specific growth rate. Besides, E_0 represents the minimum light intensity needed for a minimum specific growth rate. μ_0 is the specific growth rate in dark.

The fourth experimental data (section 5.5.4) of light intensity and specific growth rate of *S. platensis* is shown in Figure 5-25 for different light powers (normalized value). The obtained fitting parameters of μ_{max}, K_s, E_0 and μ_0 predicted via the modified Monod model are listed in Table 5-4. It was found that the hyper red LED was the best light source for growing *S. platensis* due to the highest maximum specific growth rate (μ_{max}) and the smallest Monod constant (K_s). The effect of light spectrum on *S. platensis* can be explained by the matched absorbance area of chlorophylls a [75]. From the normalized time of 0.242 to 1, the average specific growth decreased from 0.8935 to 0.2884, as well as the Monod constant from 0.1272 to 0.02297. At the normalized time of 1, μ_0 became the minimum, which means a minimum specific growth rate occurred at a high light intensity.

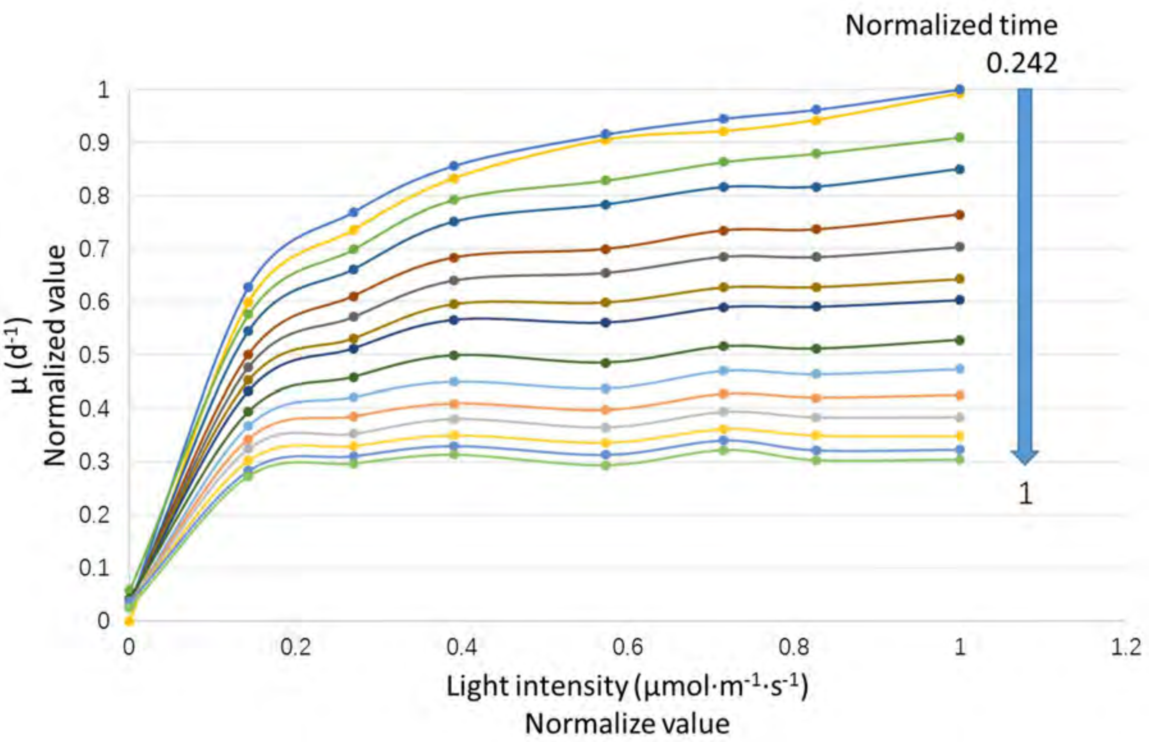


Figure 5-25 Light intensity and specific growth rate of S. platensis for the fourth experiment

Table 5-4 Fitting parameters of μ_{max}, K_s, I_0 and μ_0 predicted via the modified Monod model

Normalized time	μ_{max} (d^{-1})	K_s ($\mu mol \cdot m^{-1} \cdot s^{-1}$)	E_0 ($\mu mol \cdot m^{-1} \cdot s^{-1}$)	μ_0 (d^{-1})	R^2
0.242	0.8935	0.1272	0.006752	0.10875	0.9991
0.363	0.7051	0.09493	0.003006	0.05845	0.9988

0.687	0.3936	0.04707	0.001567	0.04914	0.9942
1	0.2884	0.02297	0.0002206	0.02818	0.9842

5.8.2 PI model analysis for photosynthetic rate

Typically, the photosynthesis irradiance (PI) curve can be divided into light-limited, light-saturated, and photo-inhibited regions. The light-limited and light-saturated regions can be characterized by three parameters: the light-limited initial slope (α^B), the light-saturated maximum photosynthetic rate (P_m^B), and the light-saturation parameter ($E_k = P_m^B/\alpha^B$) [129, 147]. Thus, the mathematical model for photosynthetic rate is described by equation 25.. P^B is the photosynthetic rate (mass-specific rate of photosynthesis) at light intensity E ; β^B is a parameter describing the reduction in photosynthetic rate at high light intensity; when β^B is negative, it means unsaturated photosynthetic rate, and the light intensity is in the light-limited region. P_s^B is a parameter equivalent to the light-saturated rate of photosynthesis (P_m^B) when β^B equals 0 [148, 149].

$$P^B = P_s^B \cdot (1 - \exp(-\alpha^B \cdot E/P_s^B)) \cdot \exp(-\beta^B \cdot E/P_s^B) \qquad 25.$$

Figure 5-25 shows the fourth experimental data of light intensity and photosynthetic rate of *S. platensis*. The obtained fitting parameters of P_s^B, α^B and β^B predicted in the model are listed in Table 5-5. The mass-specific rate of photosynthesis (P^B) had the same decreasing trend with specific growth rate (μ) from the normalized time of 0.242 to 1.

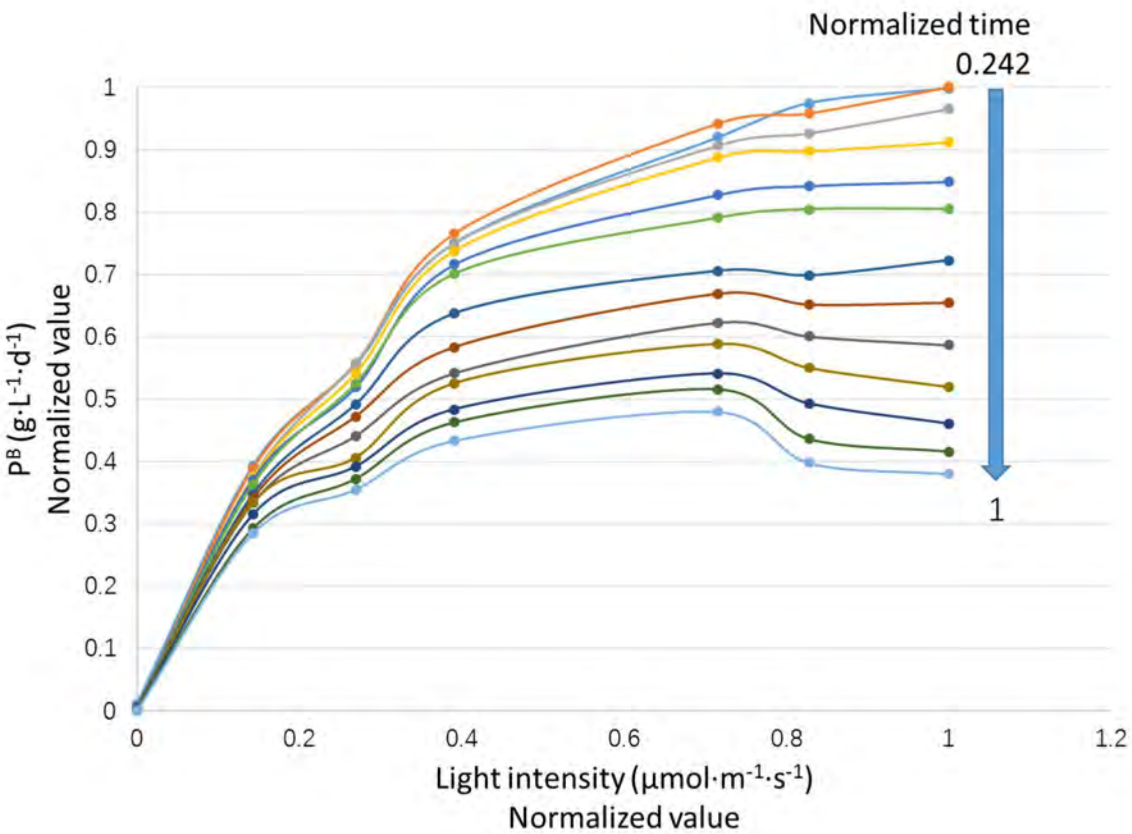


Figure 5-26 Light intensity and photosynthetic rate of S. platensis for the fourth experiment

In the case where no photo-inhibition is observed over the range of light intensities to which the cells are exposed, such β^B is identically zero, and the light-saturated rate of photosynthesis (P_m^B) happens [150]. At the normalized time of 0.242, β^B is negative, which indicates that the light intensity is not sufficient to drive the maximum photosynthetic rate, where it is in the light-limited region of PI curve. From the normalized time of 0.363, β^B is positive. A small value is indicative of strong photo-inhibition, and then P_s^B became smaller and smaller.

Table 5-5 Fitting parameters of P_s^B, α^B and β^B predicted in the model

Normalized time	P_s^B (Relative value)	α^B	β^B	R^2
0.242	1.005	3.233	-0.03766	0.9972
0.363	1.00	3.254	0.04254	0.9965
0.687	0.700	3.034	0.1027	0.9954
1	0.556	2.841	0.1798	0.9723

5.8.3 Analysis of economic efficiency for the best harvest time

As the benefits of *S. platensis* production must be estimated on the basis of energy consumption cost, it is necessary to analyze the economic efficiency of each incubator at the specific power. And it is very important to find the best harvest time at an appropriate optical density (or concentration). The economic efficiency of energy to dry biomass is defined as equation 26. [75].

$$E_{eff} = \frac{C_n - C_0}{k \cdot T \cdot P} \qquad 26.$$

Where C_n is the dry weight of biomass ($g \cdot L^{-1}$) on the nth day; k is the price of electrical power ($€ \cdot W^{-1}$); T is the time for the culture (days) and P is the power for LED supplied in each incubator (W). The relationships between economic efficiency ($g \cdot L^{-1} \cdot €^{-1}$), power (W) and time (day) are shown in Figure 5-27 and Figure 5-28.

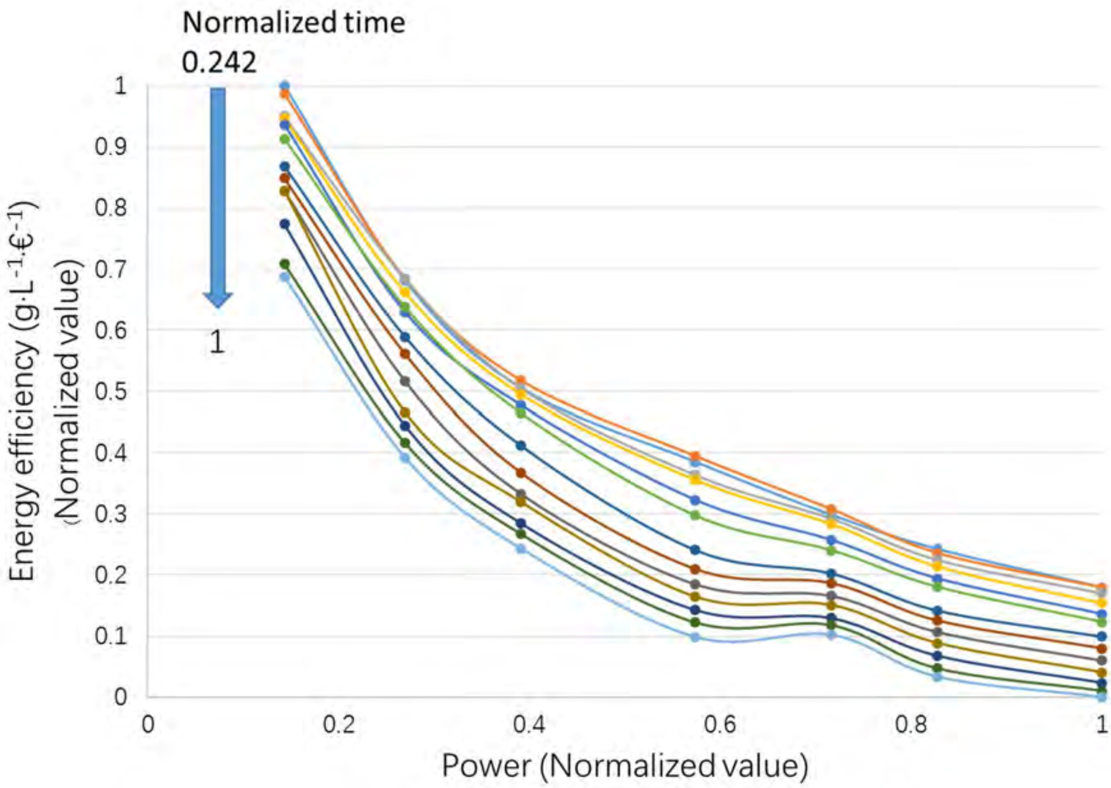


Figure 5-27 The relationship between economic efficiency and power for the fourth experiment

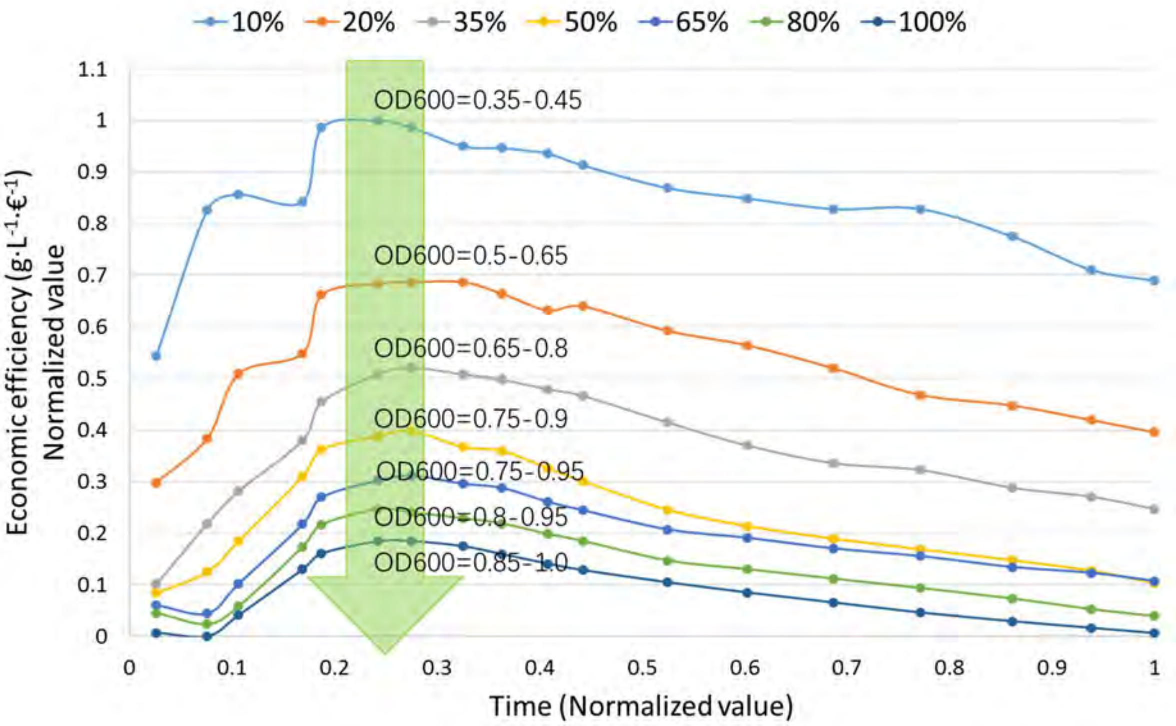


Figure 5-28 The relationship between economic efficiency and time for the fourth experiment

The results show that the maximum economic efficiency is about 1 g·L^{-1}·€$^{-1}$ at 10% maximum power at the normalized time of 0.25, after the initial photo-acclimated period. The minimum E_{eff} is 0 g·L^{-1}·€$^{-1}$ at 100% maximum power at the normalized time of 1. In conclusion, the lower the power is, the higher the economic efficiency is. The longer the cultivation is, the lower the economic efficiency is.

However, in order to find the best harvest time of *S. platensis*, the relationship between economic efficiency and time is of great significance. From Figure 5-28 we can find the maximum E_{eff} point between the normalized time of 0.2 and 0.3. The best concentration for harvest is from OD600=0.35 at 10% maximum power to OD600=1.0 at 100% maximum power. These values are not constant, because the maximum E_{eff} point changes with the environmental factors and initial concentration of *S. platensis*, so the best harvest time and OD will change accordingly.

5.9 Conclusion

In this chapter, we carried out a series of experiment to optimize the high-power LED spectra for *S. platensis* cultivation, including LED colors, efficiency, intensity, light distribution, intermittent light and light effect on phycocyanin by five ratios of red and blue photons. The comparative analysis shows that hyper red LED has the best effect on the biomass production of *S. platensis.* Blue light is conducive to improve the mass fraction of PC, but the total production per incubator is less than that under red light. Proper adjustment of the ratio between red and blue lights can achieve the desired production of PC. Two models: modified Monod model and PI model were adopted to analyze specific growth rate and photosynthetic rate. Based on the experimental results and modeling analysis, we found the maximum economic efficiency point at different power levels of LEDs, and the best harvest time at specific time and OD value.

General Conclusion and Perspectives

General conclusion

As the population of world increases continuously, people faces a variety of world crises and social issues. Healthy life and sustainable development are pursued. Modern ecological agriculture gets more attention, because it can solve or relieve many social problems such as energy crisis, environmental pollution, food security, food supply and economic woes for farmers. Controlled environment agriculture, including greenhouses and plant factories, is an important manifestation of modern agriculture. It is developing so fast that all the world uses it to reduce agricultural risk.

Artificial light technology is a core technology used in controlled environment agriculture, which can replace the unique sun light for photosynthesis. In order to overcome the defects of artificial lighting systems, characteristics and electroluminescence mechanisms of legacy and modern artificial light sources were analyzed and summed up in the first chapter. By comparison, we found LED was the ideal light source to design lighting system for plant growth.

In chapter 2, we built the temperature control box and light measurement system. Several LEDs were measured for their electrical, thermal, spectral and colorimetric characteristics. The electrical, PAR and spectral models were also analyzed, from which we found junction temperature and forward current were two key parameters for the performance of LED.

According to the parameters we tested in chapter 2, a specific LED lighting system was designed for greenhouse plants in chapter 3. We used five LED colors: red, amber, green, blue and white to match the useful spectrum for plant growth. Experimental results show that two operating modes, automatic and manual mode, can flexibly change the forward current, frequency, duty cycle and period. Power consumption is also reduced due to the efficient light spectrum. The LED lighting system can dynamically adjust the light quality, quantity and photoperiod in the practical applications.

As 5-channel LED lighting system is not able to match perfectly the RQE curve, we used Gaussian model and 12 LED spectra to theoretically find the best combination of LEDs in chapter 4, and got the corresponding proportion of each spectrum. The results show that warm white can be used as main spectrum; the others can be used as supplemental spectra. This is helpful to select the LEDs and adjust the power levels. Besides, PPF, EPPF, YPF, and the new light measurement phytometric system were described within the PAR of 400 to 700 nm. The light efficacy for each channel of LED lighting system was demonstrated by the application of five kinds of LED. The test results from specbos 1201 show that red and blue spectra have the maximum PPF, which correspond the main absorption region of chlorophyll a and b. YPF, a more accurate light measurement for plants, shows a much bigger value in the red region, which is 1.55 times as big as the YPF in the blue region. This explained why more red light was adopted than blue light in many references. Red light supplemented with a smaller amount of blue light has a great benefit for plant growth. For all the measurement, the green light has a minimum quantity. That is because much of green spectrum is reflected or transmitted by the leaves, so it is not as important as red and blue light.

In order to verify the importance of optimization of light spectrum, *S. platensis* was selected as the experimental subject in chapter 5, due to a shorter growth period as well as high nutritive and medicinal values. We focused on the impacts of different spectra for biomass production and the key pigment (phycocyanin) in *S. platensis*. A variety of LED spectral intensity and light patterns were adopted to reveal the growth parameters of *S. platensis*. The effects of red and blue light on phycocyanin were studied. Five different ratios of red and blue photons: 4:0, 3:1, 2:2, 1:3 and 0:4 were used in the experiment. It is concluded that blue light contributes to the maximum mass fraction of phycocyanin, but the total production is less than that of red light. Mathematical models were used to reveal growth regularity of specific growth rate and photosynthetic rate under different light conditions. Through comparative analysis, the results show that hyper red got the best performance. The maximum economic efficiency point was between the normalized time of 0.2 and 0.3. And the best concentration for harvest was from OD600=0.35 at 10% maximum power to OD600=1.0 at 100% maximum power. The experimental methods and results could be used as a reference to optimize a LED lighting system and select the optimal spectrum for industrial production of *S. platensis* and phycocyanin.

Future works

Future works are recommended to further optimize lighting systems for plant (algae) growth in a controlled environment. Take advantage of narrow LED spectrum, reveal the photobiology mechanism under different spectra for different species, and provide the basis for optimal lighting systems and optimal light spectrum. This study has great significance to develop modern ecological agriculture. For optimization of spectrum adapted to plants or algae, here is some suggestions for future work:

1. Design LED lighting system with more channels for different LEDs; 12 channels can realize good RQE curve;
2. Design LED lighting system with higher frequency (more than 100KHz) to find more efficient light for photosynthesis and save energy;
3. Study of monochromatic spectrum in a wide range from 300 to 800 nm; in this study hyper red was considered as the optimal spectrum for *spirulina* growth, however, there may be other adjacent wavelengths that better suit *spirulina*;
4. Study of multi-spectra combined by monochromatic light to verify Emerson effect on *spirulina* cultivation;

5. Study of intermittent spectrum with different frequencies and duty cycles to find the best light pattern for specific plants.

Annexes

List of Figures

List of Tables

References

[1] P. Gerland, A. E. Raftery, H. Sevcikova, N. Li, D. Gu, T. Spoorenberg, *et al.*, "World population stabilization unlikely this century," *Science,* vol. 346, pp. 234-7, Oct 10 2014.

[2] T. G. S. Crisis, "The State of Food Insecurity in the World," 2015.

[3] P. Shetty, "Achieving the goal of halving global hunger by 2015," *Proceedings of the Nutrition Society,* vol. 65, pp. 7-18, 2007.

[4] R. Labonte and T. Schrecker, "Committed to health for all? How the G7/G8 rate," *Soc Sci Med,* vol. 59, pp. 1661-76, Oct 2004.

[5] N. sanlier, "The knowledge and practice of food safety by young and adult consumers," *Food Control,* vol. 20, pp. 538-542, 2009.

[6] B. J. McCabe-Sellers and S. E. Beattie, "Food safety: emerging trends in foodborne illness surveillance and prevention," *J Am Diet Assoc,* vol. 104, pp. 1708-17, Nov 2004.

[7] B. A. Almanza and M. S. Nesmith, "Food safety certification regulations in the United States," *Journal of Environmental Health,* vol. 66, p. 10, 2004.

[8] D. G. Newell, M. Koopmans, L. Verhoef, E. Duizer, A. Aidara-Kane, H. Sprong, *et al.*, "Food-borne diseases - the challenges of 20 years ago still persist while new ones continue to emerge," *Int J Food Microbiol,* vol. 139 Suppl 1, pp. S3-15, May 30 2010.

[9] C. E. Handford, C. T. Elliott, and K. Campbell, "A review of the global pesticide legislation and the scale of challenge in reaching the global harmonization of food safety standards," *Integr Environ Assess Manag,* vol. 11, pp. 525-36, Oct 2015.

[10] M. Iguchi and M. Koga, "12 The state of environment and energy governance in Japan," *Environmental Challenges and Governance: Diverse Perspectives from Asia,* vol. 37, p. 219, 2015.

[11] M. Kaji, "Role of experts and public participation in pollution control: the case of Itai-itai disease in Japan<sup>1," *Ethics in Science and Environmental Politics,* vol. 12, pp. 99-111, 2012.

[12] B. Chen, W. Zheng, Y. Yu, W. Huang, S. Zheng, Y. Zhang, *et al.*, "Class 1 integrons, selected virulence genes, and antibiotic resistance in Escherichia coli isolates from the Minjiang River, Fujian Province, China," *Appl Environ Microbiol,* vol. 77, pp. 148-55, Jan 2011.

[13] R. Marti, A. Scott, Y.-C. Tien, R. Murray, L. Sabourin, Y. Zhang, *et al.*, "Impact of manure fertilization on the abundance of antibiotic-resistant bacteria and frequency of detection of antibiotic resistance genes in soil and on vegetables at harvest," *Applied and environmental microbiology,* vol. 79, pp. 5701-5709, 2013.

[14] H. Heuer, H. Schmitt, and K. Smalla, "Antibiotic resistance gene spread due to manure application on agricultural fields," *Curr Opin Microbiol,* vol. 14, pp. 236-43, Jun 2011.

[15] "The Global Social Crisis," 2011.

[16] Idrees, Muhammad. "Making biofuels from microalgae-A review of technologies." Journal of Food Science and Technology 1.2 (2014): 007-014.

[17] Dukiya, J. J. "Energy Shortage, Climate Change and the Challenge of Intelligent Transport System (ITS) Adaption in African Countries.".

[18] "http://www.esrl.noaa.gov/gmd/ccgg/trends/full.html."

[19] Seinfeld, John H., and Spyros N. Pandis. Atmospheric chemistry and physics: from air pollution to climate change. John Wiley & Sons, 2016.

[20] M. Kampa and E. Castanas, "Human health effects of air pollution," *Environ Pollut,* vol. 151, pp. 362-7, Jan 2008.

[21] Dale, Spencer. "Energy in 2015: A year of plenty." (2016).

[22] "https://www3.epa.gov/climatechange/ghgemissions/global.html."

[23] S. I. Seneviratne, M. G. Donat, A. J. Pitman, R. Knutti, and R. L. Wilby, "Allowable CO2 emissions based on regional and impact-related climate targets," *Nature,* vol. 529, pp. 477-483, 2016.

[24] Halsall, Ian L. "Towards a Sustainable Energy Economy–The Role of Palm." Journal of Oil Palm, Environment and Health (JOPEH) 2 (2012).

[25] S. G. o. i. a. I. e. A. a. f. s. u. g. r.-. Samreen.

[26] BP Statistical Review of World Energy June 2016, Available at http://bp.com/statisticalreview#BPstats.

[27] Borbitskaya, T. A., S. V. Khatskevich, and S. A. Kozlova. "Prospects of using fossil fuels." (2015).

[28] S. R. Koshti A, Naik B, et al. , "HYDROGEN FUEL CELL TECHNOLOGY AND ITS IMPACT ON AUTOMOBILE INDUSTRY ".

[29] "https://www.ecotricity.co.uk/our-green-energy/energy-independence/the-end-of-fossil-fuels."

[30] Ponce, Pedro, et al. Greenhouse Design and Control. CRC Press, 2014.

[31] Z. H. Bian, Q. C. Yang, and W. K. Liu, "Effects of light quality on the accumulation of phytochemicals in vegetables produced in controlled environments: a review," *J Sci Food Agric,* vol. 95, pp. 869-77, Mar 30 2015.

[32] T. Kozai, "Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory," *Proceedings of the Japan Academy, Series B,* vol. 89, pp. 447-461, 2013.

[33] L. Xu, H. Zheng, L. Yu, and Y. Tang, "Application and Development of Protected Horticulture Intelligent Monitoring System," *Agricultural Science & Technology,* vol. 15, p. 512, 2014.

[34] V. Ngo, S. Chung, J. Choi, S. Park, S. Kim, D. Ryu*, et al.*, "Control of temperature, humidity, and co2 concentration in small-sized experimental plant factory," in *International Symposium on New Technologies for Environment Control, Energy-Saving and Crop Production in Greenhouse and Plant 1037*, 2013, pp. 477-484.

[35] P. S. Birthal, "Application of frontier technologies for agricultural development," *Indian Journal of Agricultural Economics,* vol. 68, pp. 20-38, 2013.

[36] Zhu, Xianli, et al. "Technologies for Climate Change Adaptation-Agriculture Sector." (2011).

[37] L. Xu, S. Cao, J. Wang, and A. Lu, "Which Factors Determine Metal Accumulation in Agricultural Soils in the Severely Human-Coupled Ecosystem?," *Int J Environ Res Public Health,* vol. 13, 2016.

[38] Y. Rajesh and Y. Nita, "NEED AND NECESSITY OF GREENHOUSE EFFECT-A REVIEW," *European Journal of Biomedical AND Pharmaceutical sciences,* vol. 3, pp. 167-175, 2016.

[39] Kozai, Toyoki, Genhua Niu, and Michiko Takagaki, eds. Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production. Academic Press, 2015.

[40] W. K. Liu and Q. C. Yang, "Insights into Some Key Technological Issues on LED Lighting in Plant Factory," *China Illuminating Engineering Journal,* vol. 26, pp. 98-102, 2015.

[41] W. K. Liu and Q. C. Yang, "Intelligent Control Strategy of LED lighting in Plant Factory," *China Illuminating Engineering Journal,* vol. 25, pp. 6-8, 2014.

[42] W. K. Liu and Q. C. Yang, "Development Status of Plant Photobiology with LED Monochromatic Light and Plant Factory," *Science & Technology Review,* vol. 32, pp. 25-28, 2014.

[43] M. D. Sardare and S. V. Admane, "A review on plant without soil-hydroponics," *Int. J. Res. Eng. Technol.,* vol. 2, pp. 299-304, 2013.

[44] L. Muqing and Z. Xuesong, "Points of Several Key Issues on Agricultural Lighting," *China Light and Lighting,* pp. 1-4, 2015.

[45] Moreira, Adriano JC, Rui T. Valadas, and A. M. de Oliveira Duarte. "Optical interference produced by artificial light." Wireless Networks 3.2 (1997): 131-140.

[46] A. M. Bagher, "A Detailed Review on Types of lamps and their applications," J. of Physical and Chemical Sciences, vol. 4, 2016.

[47] Waide, Paul. "Phase out of incandescent lamps." (2010).

[48] "http://www.edisontechcenter.org/Fluorescent.html."

[49] Sağlam, Şafak, and Bülent Oral. "Modern lighting sources and controls for energy efficient lighting and a smart control algorithm application." environment 10 (2010): 11.

[50] B. Cook, "New developments and future trends in high-efficiency lighting," *Engineering Science and Education Journal,* vol. 9, pp. 207-217, 2000.

[51] "http://www.edisontechcenter.org/metalhalide.html."

[52] W. Keeffe, "Recent progress in metal halide discharge-lamp research," *IEE Proceedings A-Physical Science, Measurement and Instrumentation, Management and Education-Reviews,* vol. 127, pp. 181-189, 1980.

[53] M. Sugiura, "Review of metal-halide discharge-lamp development 1980-1992," *IEE Proceedings A-Science, Measurement and Technology,* vol. 140, pp. 443-449, 1993.

[54] R. Tiedt, H. Weske, K. Maekawa, and J. Doi, "High-pressure discharge lamp having a ceramic discharge vessel, sintered body suitable therefor, and method for producing the sintered body," ed: Google Patents, 1997.

[55] R. Apetz and M. P. Bruggen, "Transparent Alumina: A Light - Scattering Model," *Journal of the American Ceramic Society,* vol. 86, pp. 480-486, 2003.

[56] C. M. Bourget, "An introduction to light-emitting diodes," *HortScience,* vol. 43, pp. 1944-1946, 2008.

[57] R. Huber, "Thermal management of golden DRAGON LED," *Application Note, Osram Opto Semiconductors,* pp. 1-11, 2008.

[58] Bourget, C. Michael. "An introduction to light-emitting diodes." HortScience 43.7 (2008): 1944-1946.

[59] E. F. Schubert, and Jong Kyu Kim. "Solid-state light sources getting smart." Science 308.5726 (2005): 1274-1278.

[60] "http://www.edisontechcenter.org/LED.html."

[61] P. S. Schulze, L. A. Barreira, H. G. Pereira, J. A. Perales, and J. C. Varela, "Light emitting diodes (LEDs) applied to microalgal production," *Trends Biotechnol,* vol. 32, pp. 422-30, Aug 2014.

[62] M.-H. Chang, D. Das, P. V. Varde, and M. Pecht, "Light emitting diodes reliability review," *Microelectronics Reliability,* vol. 52, pp. 762-782, 2012.

[63] S. Chang, "LED lighting: high efficiency and environmental benefit," *Samsung Economic Research Institute Economic Focus, Seoul, South Korea,* pp. 1-10, 2008.

[64] B. Geffroy, P. le Roy, and C. Prat, "Organic light-emitting diode (OLED) technology: materials, devices and display technologies," *Polymer International,* vol. 55, pp. 572-582, 2006.

[65] Y.-J. Lee, S.-H. Kim, J. Huh, G.-H. Kim, Y.-H. Lee, S.-H. Cho*, et al.*, "A high-extraction-efficiency nanopatterned organic light-emitting diode," *Applied Physics Letters,* vol. 82, p. 3779, 2003.

[66] S. Reineke, F. Lindner, G. Schwartz, N. Seidler, K. Walzer, B. Lussem*, et al.*, "White organic light-emitting diodes with fluorescent tube efficiency," *Nature,* vol. 459, pp. 234-8, May 14 2009.

[67] Wheeler, Raymond M. "A historical background of plant lighting: an introduction to the workshop." HortScience 43.7 (2008): 1942-1943.

[68] Morrow R C. "LED lighting in horticulture[J]". HortScience, 2008, 43(7): 1947-1950.

[69] M. LIU and X. ZHU, "Points of Several Key Issues on Agricultural Lighting," *CHINA LIGHT & LIGHTING,* pp. 1-4, 2015.

[70] Z. Xuesong and L. Muqing, "A Preliminary Discuss of the Effects of Light on Plant Growth," *Light and Lighting,* vol. 40, pp. 1-4, 2016.

[71] http://www.ourled.com/pf.html.

[72] M. A. B. Habib, M. Parvin, T. C. Huntington, and M. R. Hasan, *A review on culture, production and use of spirulina as food for humans and feeds for domestic animals and fish*: Food and agriculture organization of the united nations, 2008.

[73] S.-H. Lee, J. E. Lee, Y. Kim, and S.-Y. Lee, "The Production of High Purity Phycocyanin by Spirulina platensis Using Light-Emitting Diodes Based Two-Stage Cultivation," *Applied biochemistry and biotechnology,* vol. 178, pp. 382-395, 2016.

[74] H.-B. Chen, J.-Y. Wu, C.-F. Wang, C.-C. Fu, C.-J. Shieh, C.-I. Chen*, et al.*, "Modeling on chlorophyll a and phycocyanin production by Spirulina platensis under various light-emitting diodes," *Biochemical Engineering Journal,* vol. 53, pp. 52-56, 2010.

[75] C.-Y. Wang, C.-C. Fu, and Y.-C. Liu, "Effects of using light-emitting diodes on the cultivation of Spirulina platensis," *Biochemical Engineering Journal,* vol. 37, pp. 21-25, 2007.

[76] A. Kumari, A. K. Pathak, and C. Guria, "Effect of light emitting diodes on the cultivation ofSpirulina platensisusing NPK-10:26:26 complex fertilizer," *Phycological Research,* vol. 63, pp. 274-283, 2015.

[77] J. P. Estrada, P. B. Bescos, and A. V. Del Fresno, "Antioxidant activity of different fractions of Spirulina platensis protean extract," *Il farmaco,* vol. 56, pp. 497-500, 2001.

[78] P. Das, W. Lei, S. S. Aziz, and J. P. Obbard, "Enhanced algae growth in both phototrophic and mixotrophic culture under blue light," *Bioresource Technology,* vol. 102, pp. 3883-3887, 2011.

[79] J. Chonko, "Using forward voltage to measure semiconductor junction temperature," *Keithley Instruments, Inc,* pp. 1-3, 2006.

[80] S. Chhajed, Y. Xi, T. Gessmann, J.-Q. Xi, J. M. Shah, J. K. Kim*, et al.*, "Junction temperature in light-emitting diodes assessed by different methods," in *Integrated Optoelectronic Devices 2005*, 2005, pp. 16-24.

[81] B. Siegal, "Practical considerations in high power LED junction temperature measurements," in *Electronics Manufacturing and Technology, 31st International Conference on*, 2007, pp. 62-66.

[82] Y. Gu and N. Narendran, "A noncontact method for determining junction temperature of phosphor-converted white LEDs," in *Optical Science and Technology, SPIE's 48th Annual Meeting*, 2004, pp. 107-114.

[83] Y. Xi and E. Schubert, "Junction-temperature measurement in GaN ultraviolet light-emitting diodes using diode forward voltage method," *Applied Physics Letters,* vol. 85, pp. 2163-2165, 2004.

[84] A. Keppens, W. Ryckaert, G. Deconinck, and P. Hanselaer, "High power light-emitting diode junction temperature determination from current-voltage characteristics," *Journal of Applied Physics,* vol. 104, p. 093104, 2008.

[85] M.-C. Chien and C.-H. Tien, "Multispectral mixing scheme for LED clusters with extended operational temperature window," *Optics express,* vol. 20, pp. A245-A254, 2012.

[86] T. Khan and P. Bodrogi, *LED lighting: technology and perception*: John Wiley & Sons, 2015.

[87] M. K. J., "The action spectrum, absorptance and quantum yield of photosynthesis in crop plants," *Agric. Meteorol. ,* vol. 9, pp. 191-216, 1972a. .

[88] J. Whitmarsh, "The photosynthetic process," in *Concepts in Photobiology*, ed: Springer, 1999, pp. 11-51.

[89] Yorio N C, Goins G D, Kagie H R, and e. al, "Improving spinach, radish, and lettuce growth under red light-emitting diodes (LEDs) with blue light supplementation," *HortScience,* vol. 36, pp. 380-383, 2001.

[90] S. W. Hogewoning, G. Trouwborst, H. Maljaars, H. Poorter, W. van Ieperen, and J. Harbinson, "Blue light dose-responses of leaf photosynthesis, morphology, and chemical composition of Cucumis sativus grown under different combinations of red and blue light," *J Exp Bot,* vol. 61, pp. 3107-17, Jun 2010.

[91] C.-C. Chen, M.-Y. Huang, K.-H. Lin, S.-L. Wong, W.-D. Huang, and C.-M. Yang, "Effects of light quality on the growth, development and metabolism of rice seedlings (Oryza sativa L.)," *Research Journal of Biotechnology,* vol. 9, pp. 15-24, 2014.

[92] P. H. Moon, "Scientific basis of illuminating engineering," 1936.

[93] G. J. da Costa and J. L. Cuello, "The Phytometric System: A new concept of light measurement for plants," *Journal of the Illuminating Engineering Society,* vol. 33, pp. 34-42, 2004.

[94] P. Halldal, "Ultraviolet action spectra of photosynthesis and photosynthetic inhibition in a green and a red alga," *Physiologia plantarum,* vol. 17, pp. 414-421, 1964.

[95] T. Tanada, "The photosynthetic efficiency of carotenoid pigments in Navicula minima," *American Journal of Botany,* pp. 276-283, 1951.

[96] F. T. Haxo and L. Blinks, "Photosynthetic action spectra of marine algae," *The Journal of general physiology,* vol. 33, pp. 389-422, 1950.

[97] E. I. Rabinowitch, "Photosynthesis and Related Processes," *Soil science,* vol. 72, p. 482, 1951.

[98] K. Inada, "Action spectra for photosynthesis in higher plants," *Plant and Cell Physiology,* vol. 17, pp. 355-365, 1976.

[99] J. Sager, J. Edwards, and W. Klein, "Light energy utilization efficiency for photosynthesis," *Transactions of the ASAE,* vol. 25, pp. 1737-1746, 1982.

[100] R. J. Woodham, "Photometric method for determining surface orientation from multiple images," *Optical engineering,* vol. 19, pp. 191139-191139-, 1980.

[101] H. M. Cathey and L. E. Campbell, "Light and lighting systems for horticultural plants," *Horticultural Reviews, Volume 2,* pp. 491-537, 1980.

[102] C. DeCusatis, *Handbook of applied photometry*: American Inst. of Physics, 1997.

[103] G. Wyszecki and W. S. Stiles, *Color science* vol. 8: Wiley New York, 1982.

[104] J. Sager, W. Smith, J. Edwards, and K. Cyr, "Photosynthetic efficiency and phytochrome photoequilibria determination using spectral data," *Transactions of the ASAE,* vol. 31, pp. 1882-1889, 1988.

[105] J. U. Grobbelaar, "Mass production of microalgae at optimal photosynthetic rates," *Photosynthesis. InTech,* vol. 558, p. 559, 2013.

[106] R. P. Bezerra, M. C. Matsudo, A. Converti, S. Sato, and J. C. de Carvalho, "Influence of ammonium chloride feeding time and light intensity on the cultivation of Spirulina (Arthrospira) platensis," *Biotechnol Bioeng,* vol. 100, pp. 297-305, Jun 1 2008.

[107] A. Morist, J. Montesinos, J. Cusido, and F. Godia, "Recovery and treatment of Spirulina platensis cells cultured in a continuous photobioreactor to be used as food," *Process Biochemistry,* vol. 37, pp. 535-547, 2001.

[108] G. Chamorro, M. Salazar, K. Araujo, C. Dos Santos, G. Ceballos, and L. F. Castillo, "[Update on the pharmacology of Spirulina (Arthrospira), an unconventional food]," *Archivos latinoamericanos de nutrición,* vol. 52, pp. 232-240, 2002.

[109] K. Kato, K. Takemoto, H. Katayama, and Y. Kuwabara, "Effects of Spirulina (Spirulina platensis) on dietary hypercholesterolemia in rats," *Journal of Japanese Society of Nutrition and Food Science (Japan),* 1984.

[110] M. Anusuya Devi and L. VENKATARAM, "Hypocholesterolemic effect of blue green algae Spirulina platensis in albino rats," *Nutrition reports international,* vol. 28, pp. 519-530, 1983.

[111] W.-L. Chu, Y.-W. Lim, A. K. Radhakrishnan, and P.-E. Lim, "Protective effect of aqueous extract from Spirulina platensis against cell death induced by free radicals," *BMC complementary and alternative medicine,* vol. 10, p. 53, 2010.

[112] M. Miranda, R. Cintra, S. Barros, and J. Mancini-Filho, "Antioxidant activity of the microalga Spirulina maxima," *Brazilian Journal of Medical and biological research,* vol. 31, pp. 1075-1079, 1998.

[113] R. Deng and T. J. Chow, "Hypolipidemic, antioxidant, and antiinflammatory activities of microalgae Spirulina," *Cardiovascular therapeutics,* vol. 28, pp. e33-e45, 2010.

[114] P. C. Dartsch, "Antioxidant potential of selected Spirulina platensis preparations," *Phytotherapy Research,* vol. 22, pp. 627-633, 2008.

[115] A. Belay, Y. Ota, K. Miyakawa, and H. Shimamatsu, "Current knowledge on potential health benefits of Spirulina," *Journal of applied Phycology,* vol. 5, pp. 235-241, 1993.

[116] D. Vijayarani, S. Ponnalaghu, and J. Rajathivya, "Development of Value Added Extruded Product Using Spirulina," *International Journal of Health Sciences and Research,* vol. 2, pp. 42-47, 2012.

[117] V. B. Bhat and K. Madyastha, "C-phycocyanin: a potent peroxyl radical scavenger in vivo and in vitro," *Biochemical and biophysical research communications,* vol. 275, pp. 20-25, 2000.

[118] A. C. Schuerger, C. S. Brown, and E. C. Stryjewski, "Anatomical features of pepper plants (Capsicum annuum L.) grown under red light-emitting diodes supplemented with blue or far-red light," *Annals of Botany,* vol. 79, pp. 273-282, 1997.

[119] D. J. Tennessen, E. L. Singsaas, and T. D. Sharkey, "Light-emitting diodes as a light source for photosynthesis research," *Photosynthesis research,* vol. 39, pp. 85-92, 1994.

[120] Renewable biological systems for unsustainable energy production, FAO Agricultural Services Bulletins, 1997.

[121] J. M. Pisciotta, Y. Zou, and I. V. Baskakov, "Light-dependent electrogenic activity of cyanobacteria," *PloS one,* vol. 5, p. e10821, 2010.

[122] P. H. Ravelonandro, D. H. Ratianarivo, C. Joannis ‐ Cassan, A. Isambert, and M. Raherimandimby, "Influence of light quality and intensity in the cultivation of

Spirulina platensis from Toliara (Madagascar) in a closed system," *Journal of Chemical Technology and Biotechnology,* vol. 83, pp. 842-848, 2008.

[123] A. Bricaud, M. Babin, A. Morel, and H. Claustre, "Variability in the chlorophyll‐specific absorption coefficients of natural phytoplankton: Analysis and parameterization," *Journal of Geophysical Research: Oceans,* vol. 100, pp. 13321-13332, 1995.

[124] P. H. Raven, R. F. Evert, and S. E. Eichhorn, *Biology of plants*: Macmillan, 2005.

[125] A. J. Young, "The photoprotective role of carotenoids in higher plants," *Physiologia Plantarum,* vol. 83, pp. 702-708, 1991.

[126] H. A. Frank and R. J. Cogdell, "Carotenoids in photosynthesis," *Photochemistry and photobiology,* vol. 63, pp. 257-264, 1996.

[127] E. Gantt, "Structure and function of phycobilisomes: light harvesting pigment complexes in red and blue-green algae," *International Review of Cytology,* vol. 66, pp. 45-80, 1980.

[128] C. Lemasson, N. T. De Marsac, and G. Cohen-Bazire, "Role of allophycocyanin as light-harvesting pigment in cyanobacteria," *Proceedings of the National Academy of Sciences,* vol. 70, pp. 3130-3133, 1973.

[129] H. L. MacIntyre, T. M. Kana, T. Anning, and R. J. Geider, "Photoacclimation of photosynthesis irradiance response curves and photosynthetic pigments in microalgae and cyanobacteria1," *Journal of phycology,* vol. 38, pp. 17-38, 2002.

[130] J. U. Grobbelaar, "Photosynthetic response and acclimation of microalgae to light fluctuations," *Algal cultures analogues of blooms and applications. Science Publishers, Enfield, NH, USA,* pp. 671-683, 2006.

[131] M. J. Behrenfeld, O. Prasil, Z. S. Kolber, M. Babin, and P. G. Falkowski, "Compensatory changes in photosystem II electron turnover rates protect photosynthesis from photoinhibition," *Photosynthesis Research,* vol. 58, pp. 259-268, 1998.

[132] N. Murata, S. Takahashi, Y. Nishiyama, and S. I. Allakhverdiev, "Photoinhibition of photosystem II under environmental stress," *Biochimica et Biophysica Acta (BBA)-Bioenergetics,* vol. 1767, pp. 414-421, 2007.

[133] O. Prasil, N. Adir, and I. Ohad, "Dynamics of photosystem II: mechanism of photoinhibition and recovery process," *Topics in photosynthesis,* vol. 11, pp. 295-348, 1992.

[134] C. Lu and A. Vonshak, "Photoinhibition in outdoor Spirulina platensis cultures assessed by polyphasic chlorophyll fluorescence transients," *Journal of Applied Phycology,* vol. 11, pp. 355-359, 1999.

[135] A. Morel and A. Bricaud, "Theoretical results concerning light absorption in a discrete medium, and application to specific absorption of phytoplankton," *Deep Sea Research Part A. Oceanographic Research Papers,* vol. 28, pp. 1375-1393, 1981.

[136] C. Zarrouk, *Contribution a L'etude D'une Cianophycee: Influence de Divers Facteurs Physiques Et Chimiques Sur la Croissance Et la Photosynthese de Spirulina Maxima (Setch. Et Garndner) Geitler*: Faculte des Sciences, Universite de Paris, 1966.

[137] J. U. Grobbelaar, L. Nedbal, L. Tichy, and L. Setlik, "Variation in some photosynthetic characteristics of microalgae cultured in outdoor thin-layered sloping reactors," *Journal of applied phycology,* vol. 7, pp. 175-184, 1995.

[138] J. U. Grobbelaar, L. Nedbal, and V. Tichý, "Influence of high frequency light/dark fluctuations on photosynthetic characteristics of microalgae photoacclimated to different light intensities and implications for mass algal cultivation," *Journal of Applied Phycology,* vol. 8, pp. 335-343, 1996.

[139] J. U. Grobbelaar, "Turbulence in mass algal cultures and the role of light/dark fluctuations," *Journal of Applied Phycology,* vol. 6, pp. 331-335, 1994.

[140] J. U. Grobbelaar, "Microalgal biomass production: challenges and realities," *Photosynthesis research,* vol. 106, pp. 135-144, 2010.

[141] D. J. Tennessen, R. J. Bula, and T. D. Sharkey, "Efficiency of photosynthesis in continuous and pulsed light emitting diode irradiation," *Photosynthesis research,* vol. 44, pp. 261-269, 1995.

[142] A. A. Lunka and D. J. Bayless, "Effects of flashing light-emitting diodes on algal biomass productivity," *Journal of applied phycology,* vol. 25, pp. 1679-1685, 2013.

[143] J. U. Grobbelaar, "Upper limits of photosynthetic productivity and problems of scaling," *Journal of applied phycology,* vol. 21, pp. 519-522, 2009.

[144] SN /T 1113—2002, Method for determination of phycocyanin and chlorophyiis in spirulina powder for import and export [S]. Standards Press of China, 2002.

[145] J. Monod, "The growth of bacterial cultures," *Annual Reviews in Microbiology,* vol. 3, pp. 371-394, 1949.

[146] D. Dochain, *On-line parameter estimation, adaptive state estimation and adaptive control of fermentation processes*: Université Catholique de Louvain, 1986.

[147] T. Platt, K. Denman, and A. Jossby, "Modelling the productivity of phytoplankton," 1977.

[148] P. Eilers and J. Peeters, "A model for the relationship between light intensity and the rate of photosynthesis in phytoplankton," *Ecological modelling,* vol. 42, pp. 199-215, 1988.

[149] A. D. Jassby and T. Platt, "Mathematical formulation of the relationship between photosynthesis and light for phytoplankton," *Limnology and oceanography,* vol. 21, pp. 540-547, 1976.

[150] T. Platt, C. Gallegos, and W. Harrison, "Photoinhibition of photosynthesis in natural assemblages of marine phytoplankton," 1981.

Résumé

Les systèmes d'éclairage artificiels sont couramment utilisés pour la croissance des plantes en serre ou environnement contrôlé (culture hydroponique, hors sol, etc…). Leur principale fonction est d'améliorer la qualité et la quantité de la production agricole indépendamment des saisons et de l'ensoleillement. L'utilisation d'une source de rayonnement artificielle pour plantes (PARS pour "Plant Artificial Radiation Sources") signifie que la lumière du soleil n'a pas été l'unique source de lumière pour la production agricole, mais qu'elle a été remplacé ou complété par une source artificielle (PARS). Les serres ou les complexes de culture hydroponique avec éclairage artificiel (Plant Factory with Artificial Lighting, "PFAL"), notamment à LED, sont une technologie innovante pour l'agriculture moderne susceptible de changer fondamentalement certains concepts.

Cependant, certaines difficultés persistent avec ces nouvelles techniques. Tout d'abord, par manque de formation ou d'information, certaines personnes ne comprennent pas les caractéristiques techniques des sources de lumière artificielle moderne. Deuxièmement, les mécanismes de photobiologie sous différents spectres sont encore mal définis en fonction des espèces de plantes. Troisièmement, le secteur agricole est une grande entité qui présente également une grande complexité de part la variabilité des cultures. En conséquence, les "PARS" ont généralement une faible efficacité et présentent une consommation énergétique élevée, ce qui devient le principal obstacle pour leur application. Les PARS et leurs systèmes sont la technique de base pour développer l'horticulture contrôlée, en particulier dans la culture hydroponique qui n'utilisent que les sources d'éclairage artificielle. Toutefois, la consommation d'énergie et les défauts de conception deviennent des difficultés rédhibitoires à leur mise en oeuvre. Par conséquent, la sélection d'une source de lumière efficace et l'optimisation des systèmes d'éclairage sont d'une grande importance. Connaître le type de spectre optimal pour une variété de plante ou d'algue nécessite donc des études plus approfondies.

Les diodes électroluminescentes (LED) pour l'éclairage constituent une source de lumière de dernière génération compatible avec les puissances lumineuses nécessaires à la croissance de plantes. Par rapport aux sources traditionnelles, elles présentent des avantages incomparables tels qu'un rendement élevé, une longue durée de vie, un rayonnement relativement simple à contrôler par rapport aux sources de lumières classiques, une lumière dite "froide" (pas d'émission infra-rouge), de petite taille, robuste, etc. En outre, les systèmes d'éclairage à LED ("LED Lighting Systems", LLS) utilisent une alimentation en courant continu, ce qui est plus fiable et plus facile à contrôler. Par conséquent, les "LLS" deviennent de plus en plus populaire pour les chercheurs, ingénieurs, fabricants, biologistes et industriels du secteur agronomique. En particulier, les applications des LEDs pour la production agricole suscitent une vive attention dans le monde ces dernières années. Les sources de lumière à LED sont connues comme étant le choix idéal en horticulture sous conditions contrôlées (notamment vis-à-vis de leur faible consommation énergétique).

Dans cette étude, nous aborderons principalement les nouvelles techniques "PARS" et "PFAL" comme facteurs environnementaux de base pour la croissance des plantes. Sur la base des caractéristiques des LEDs et du rayonnement photosynthétique actif (Photosynthetically Active Radiation, PAR), un système spécifique à base de LED a été conçu pour la croissance des plantes. Celui-ci peut ajuster dynamiquement la qualité, la quantité et la photopériode. Le spectre optimal pour une plante « standard » a été simulé et optimisé sur la base de rendement quantique relatif (Relative Quantum Efficiency, RQE). Nous avons étudié en particulier la spiruline en raison de son court cycle de vie mais aussi pour ses qualités nutritionnelles et médicinales. Enfin, nous avons concentré notre étude sur les impacts des spectres bleu et rouge pour la production de biomasse et du pigment clé (phycocyanine) de la spiruline.